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AMORPHOUS SILICON SOLAR CELL RELIABILITY RESEARCH

FINAL REPORT
SEPTEMBER 1986

J.W. LATHROP

PREPARED FOR:
JET PROPULSION LABORATORY

PREPARED BY:
CLEMSON UNIVERSITY

CENTER FOR SEMICONDUCTOR DEVICE RELIABILITY RESEARCH

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ENGINEERING AREA

AMORPHOUS SILICON SOLAR CELL RELIABILITY RESEARCH

INVESTIGATION OF ACCELERATED STRESS FACTORS AND FAILURE/DEGRADATION MECHANISMS IN TERRESTRIAL SOLAR CELLS

FINAL REPORT

J.W. Lathrop

Center for Semiconductor Device Reliability Research
Clemson University, Clemson, SC 29634-0915

September 1986

The JPL Flat-Plate Solar Array Project is sponsored by the U.S. Department of Energy and is part of the Photovoltaic Energy Systems Program to initiate a major effort toward the development of cost-competitive solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology by agreement between NASA and DOE.

CLEMSON PERSONNEL

Persons contributing to the program since the issuance of the previous (Sixth) Annual Report include:

Dr. Jay W. Lathrop	Principal Investigator
Mr. Dexter C. Hawkins	Research Associate
Ms. Lai K. Chan	Graduate Student (MS)
Ms. Clara White Davis	Graduate Student (PhD)
Mr. Patrick L. Hefley	Graduate Student (MS)
Mr. James A. Bost	Undergraduate Student
Mr. Wendell E. Jones, Jr.	Undergraduate Student
Mr. Kerry H. Wheeles	Undergraduate Student

ACKNOWLEDGEMENT

The Jet Propulsion Laboratory Technical Manager for most of the 8 1/2 years that the reliability program at Clemson has been in force was Mr. Edward L. Royal. His assistance in acquiring test samples and in supplying technical guidance to the program is gratefully acknowledged.

Mr. Melvin I. Smokler served as JPL Technical Manager during the program's final phase and it was as a result of his efforts that the program was able to be brought to a successful conclusion.

RESEARCH PARTNERSHIPS WITH AMORPHOUS CELL MANUFACTURERS

Clemson University is very grateful to the various cell manufacturers who entered into cooperative reliability research partnership agreements with it during the 8 1/2 years that the program was in force. The cooperation shown by these manufacturers in supplying cells and reviewing test results indicates their interest in producing cells of the highest possible reliability. It is only through such cost effective research partnerships with industry that DOE sponsored research programs are able to contribute to the generic understanding of the attributes of commercially manufactured solar cells.

Cells from the following manufacturers were studied in the Clemson program:

- Applied Solar Energy -- single crystal
- Arco Solar -- single crystal and amorphous
- Chronar -- amorphous
- Mobil Solar -- EFG crystalline
- Photowatt -- single crystal
- Solarex -- single crystal and amorphous
- Solar Power -- single crystal
- Solavolt -- single crystal
- Solec -- single crystal
- Solenergy -- single crystal
- Spectrolab -- single crystal
- Spire -- single crystal
- Westinghouse -- dendritic web crystalline

ABSTRACT

This is the final report of a reliability research program to study the response of amorphous silicon colar cells to accelerated temperature testing. The goal of the research was to utilize accelerated testing to identify failure/degradation modes and to relate them to basic physical, chemical, and metallurgical phenomena. Four types of single junction commercial modules were subjected to 140 C testing, both in the dark and under illuminated conditions. The before and after electrical characteristics of individual cells were measured and compared and correlated with physical evidence. A fifth module type could not be tested because of poor adherence of the films to the glass superstrate. A short term effect of stressing was noted which dramatically improved cells with low Voc on one type of construction. All cells eventually showed long term irreversible degradation, but the time to 50% Pm reduction varied by as much as two orders of magnitude depending on construction. No basic difference could be detected between degradation under illuminated or non-illuminated conditions, when cells were either open or short circuited. Comparison with one type of tandem cell and with published results of Japanese cell testing indicated the marked superiority of the tandem cell to all other types. Cells were examined physically by optical, IR, and scanning electron microscopy and by Auger spectroscopy, secondary ion mass spectroscopy, and energy dispersive x-ray analysis. The long term degradation was felt to be due to localized penetration of aluminum through the amorphous film.

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1.0 INTRODUCTION

This is the Final Report on the Investigation of Accelerated Stress Factors and Failure/Degradation Mechanisms in Terrestrial Solar Cells, a photovoltaic cell reliability research program which has been conducted by Clemson University for the Department of Energy (DOE) Flat-Plate Solar Array (FSA) Project managed by the Jet Propulsion Laboratory. The program was initiated in December 1977 and continued until June 1986. The objective of the research was the identification and characterization of fundamental physical, chemical, and metallurgical phenomena which, acting at the cell level, could cause photovoltaic modules to degrade with time. The approach followed was to develop laboratory tests which would accelerate anticipated field failure modes, and then to subject quantities of different types of cells to these tests. Analysis of the pre- and post-stress test data, combined with visual observations, was then used in an effort to determine the nature of degradation mechanisms. Earlier reports (1,2,3,4,5,6,7) have discussed the experimental and analytical methods employed, the data collected, and a number of preliminary conclusions. The early portion of the work was devoted to determining the reliability attributes of crystalline silicon cells, with accelerated testing performed on both encapsulated and unencapsulated configurations. Starting in about 1984 the program's emphasis shifted to amorphous silicon cells and during 1985 and 1986 was devoted almost entirely to developing stress testing procedures applicable to amorphous silicon cells. This work has resulted in the presentation at international conferences of a number of papers (8,9,10,11,12,13). The most recent paper in this series, which was presented at the Second International Photovoltaic Science and

Engineering Conference in Beijing, China in August 1986 is reproduced in Appendix A.

By definition, reliability, which implies the absence of failure, involves changes that take place in "good" devices after they have been manufactured. In the usual sense, a reliability failure occurs when the characteristics of a device change in such a way as to lie outside some predefined set of specifications. The classical "bathtub" curve of failure rate vs time shown in Figure 1 consists of three regions -- an initially high failure rate which decreases with time to a lower, relatively constant rate characteristic of the device's useful life, followed by a region of increasing failure rate. Because the electrical characteristics of individual solar cells are not specified in the same sense as they are for devices such as integrated circuits, it is not possible to speak of solar cell "failures" and instead the term "degradation" is used to describe observed characteristic changes.

The three categories of degradation mechanisms for all types of semiconductor devices are: 1) wearout, 2) defect accelerated wearout, and 3) overstress induced. These three categories constitute generic areas where research is necessary if an adequate level of solar cell reliability is to be achieved and maintained.

Wearout refers to degradation of the main population of non-defective devices. Wearout mechanisms may be activated and accelerated by a number of stresses -- voltage, current, temperature, and light -- working singly or in combination. Examples of wearout mechanisms are corrosion, diffusion (intermetallic compound formation), and the formation of interface surface

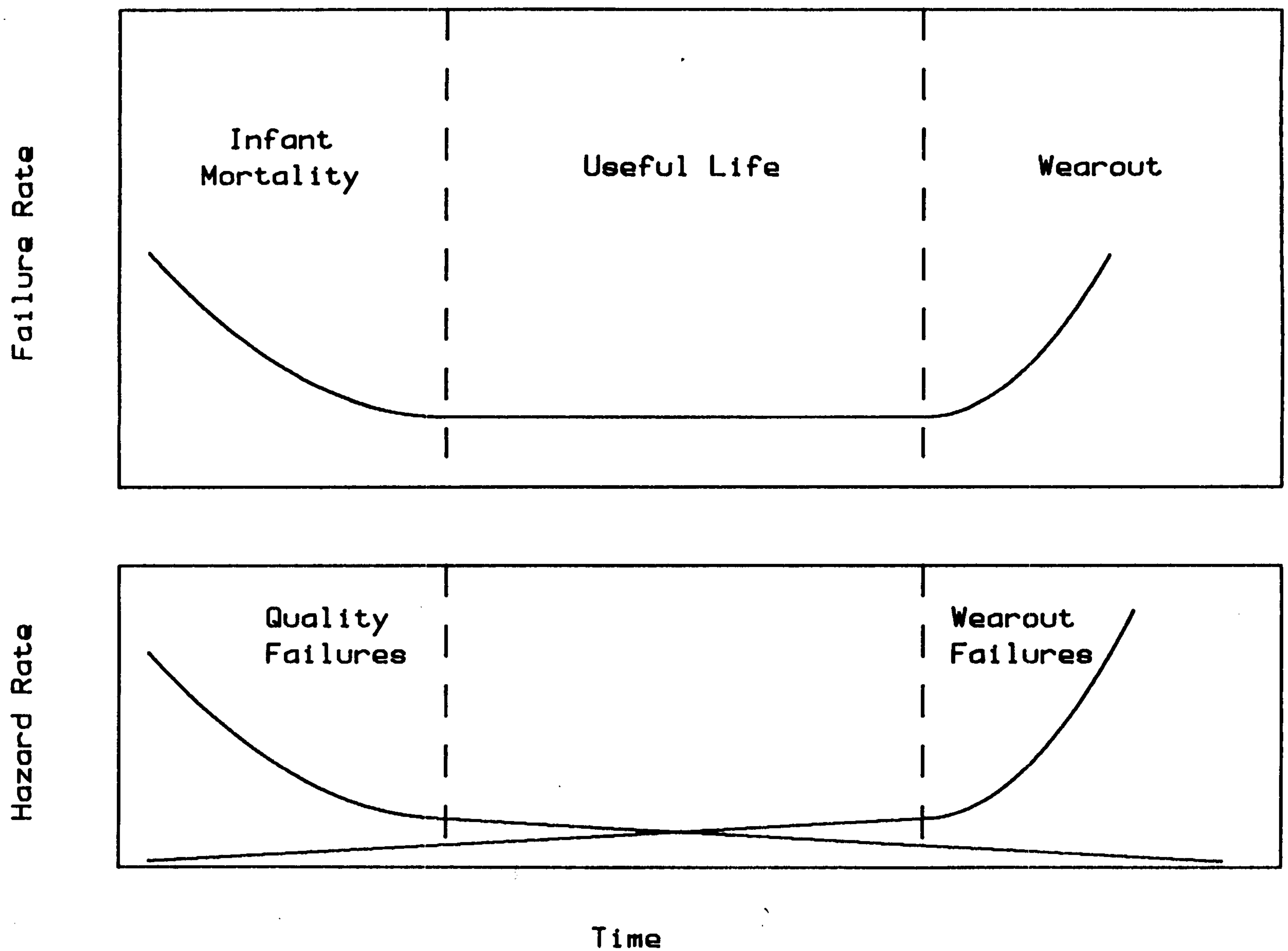


Figure 1. Classical Failure Rate vs Time Curve

states. Ideally, no appreciable wearout failures should occur prior to obsolescence. DOE reliability goals have been stated in terms of no more than 10% reduction in power output over 30 years.

Defective devices, i.e. those involving freak distributions of one or more physical parameters, will also be affected by wearout mechanisms. However, because of the presence of flaws introduced during manufacturing, defective devices will degrade faster than those of the main population resulting in "infant mortalities". Infant mortalities, which often can be attributed to workmanship type defects, are the most variable and least predictable type of failure mechanism and the major source of reliability concern for most types of electronic components. Because of the redundant wiring of most photovoltaic systems, however, even the complete degradation of a cell to an open circuit or short circuit condition will not result in a system failure, infant mortality problems are not nearly as serious. From the system standpoint, the degradation of 90% of the cells by 10% is much more serious than the degradation of 1% of the cells by 90%. Thus the major emphasis of the program has been to look for fundamental wearout type mechanisms rather than concentrating on relatively rare manufacturing defects.

There are instances, however, where manufacturing defects can involve a general loss of process control during manufacture. In this case entire lots are defective and the freak distribution referred to earlier is now the main distribution. A classic example of this type of behavior that was discovered a few years ago on crystalline cells which were receiving improper cleaning prior to plating, with the result that the grids uniformly lost adherence when subjected to accelerated testing. When this was called to the manufacturer's attention controls were instituted which corrected the problem. A more recent example is given in this report where it is seen that one group of amorphous cells show rapid and uniform degradation attributed to localized movement of indium from the ITO layer into the active cell structure whereas other groups of cells from the same manufacturer do not show degradation until much longer stress times. Although sufficient testing has not been done to determine the cause of this movement it has been confirmed by Auger analysis.

The third degradation mechanism category is that induced by overstress. Overstress may be either mechanical, thermal, or electrical. Mechanical overstress includes that due to hail and other impacts. Electrical overstress includes lightning strikes and electrical transients. Thermal overstress is usually the result of dissipating electrical energy in the reverse breakdown characteristic region (hot spot heating). The theory of reverse breakdown in terms of the thermal and electrical cell properties for flat plate encapsulated crystalline cells was the subject of a 1981 Clemson Ph.D. dissertation by R.A. Hartman (3,14). Aside from this activity, however, overstress conditions were considered to be too application specific and the program mainly concentrated on identifying and characterizing wearout mechanisms.

Accelerated test methodology involves subjecting cells to stresses higher than normally encountered in hopes that naturally occurring degradation mechanisms, which might take years to detect in the field, can be detected in the laboratory within days or weeks. Cells are initially visually inspected and electrically measured, subjected to the desired level of stress, and then measured and inspected again. Changes which occur can then be assumed to be due to the effect of stress and through analysis of the observed degradation related to fundamental physical, chemical, or metallurgical changes. In this way accelerated stress testing can be used to uncover potential failure mechanisms in a relatively short period of time, permitting preventative measures to be taken.

For accelerated testing to provide useful results, however, three conditions must be met: 1) the samples being stressed must be representative of the manufactured population, 2) a stress window must exist, and 3) the measurement methods used must have a sufficient degree of repeatability. Meeting these conditions was relatively easy for crystalline cells, but proved formidable with regard to amorphous cells. In particular, considerable effort was expended to assure measurement repeatabliity.

Previous annual reports have described in detail the instrumentation and procedures used for accelerated testing of crystalline silicon solar cells and the results obtained. Previous reports have also described the instrumentation and procedures used to test amorphous cells. Although this is a final report it is not intended to be comprehensive and this material will not be repeated. Instead the report concentrates on recent test results from amorphous cells obtained since issuance of the Sixth Annual Report in November 1985.

2.0 EXPERIMENTAL PROCEDURES FOR AMORPHOUS CELL ACCELERATED TESTING.

Sample single junction PIN modules were obtained from three different commercial manufacturers. In the series connected, monolithic type of amorphous cell construction, connection to the front of the cell under test is made from the back of an adjacent cell as shown in Figure 2(a). Test point A connects to the transparent conducting oxide of the main cell while test point B contacts the back of the main cell. The lumped constant equivalent circuit including the presence of the parasitic cell is shown in Figure 2(b). From a reliability standpoint the contact between the aluminum back metallization and the transparent conducting oxide front contact is of particular concern. If the resistance (Rc) of this contact should become too large the diode of the parasitic cell would become evident resulting in an upward curvature of the cell's fourth-quadrant IV characteristic and a reduction of Voc and consequent loss of power in the first quadrant as a result of the forward drop of the diode.

To avoid contact series resistance effects when making electrical connections to test points A and B, separate voltage and current probes (Kelvin probes) need to be used. After extensive investigation, the only technique found to be completely repeatable was to permanently attach parallel wires the length of each contact using conductive epoxy. Figure 3 illustrates the resulting epoxy pattern. The conductive epoxy used was Type K Microcircuit Silver made by Transene Co. Inc. Rowley, MA, USA. A cure cycle of 125 C for 135 minutes is required, but this additional stress was felt to be negligible compared to most accelerating stress schedules. On Cell Type "D" difficulty

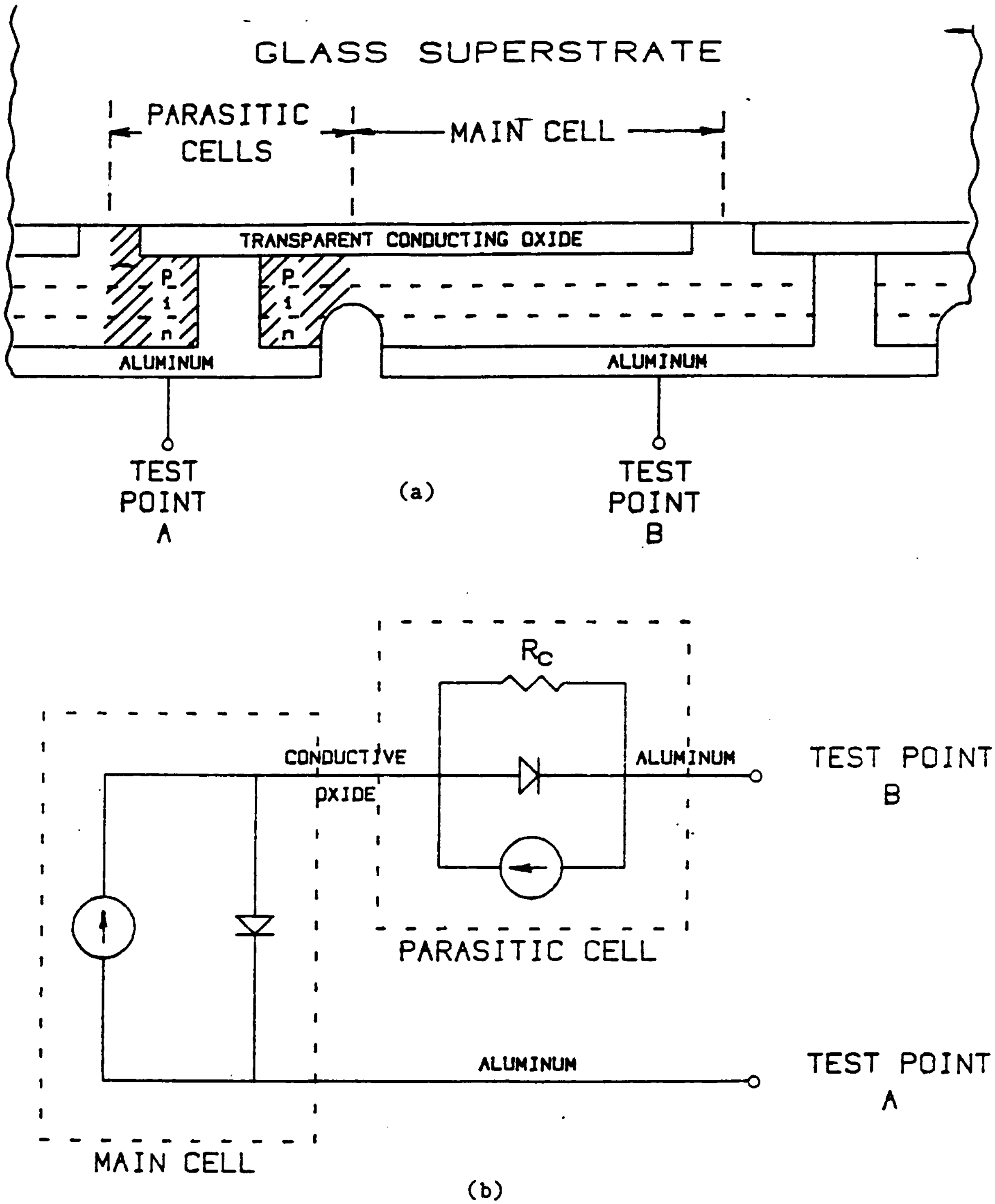


Figure 2. Equivalent Circuit of Series Connected Thin Film Cell

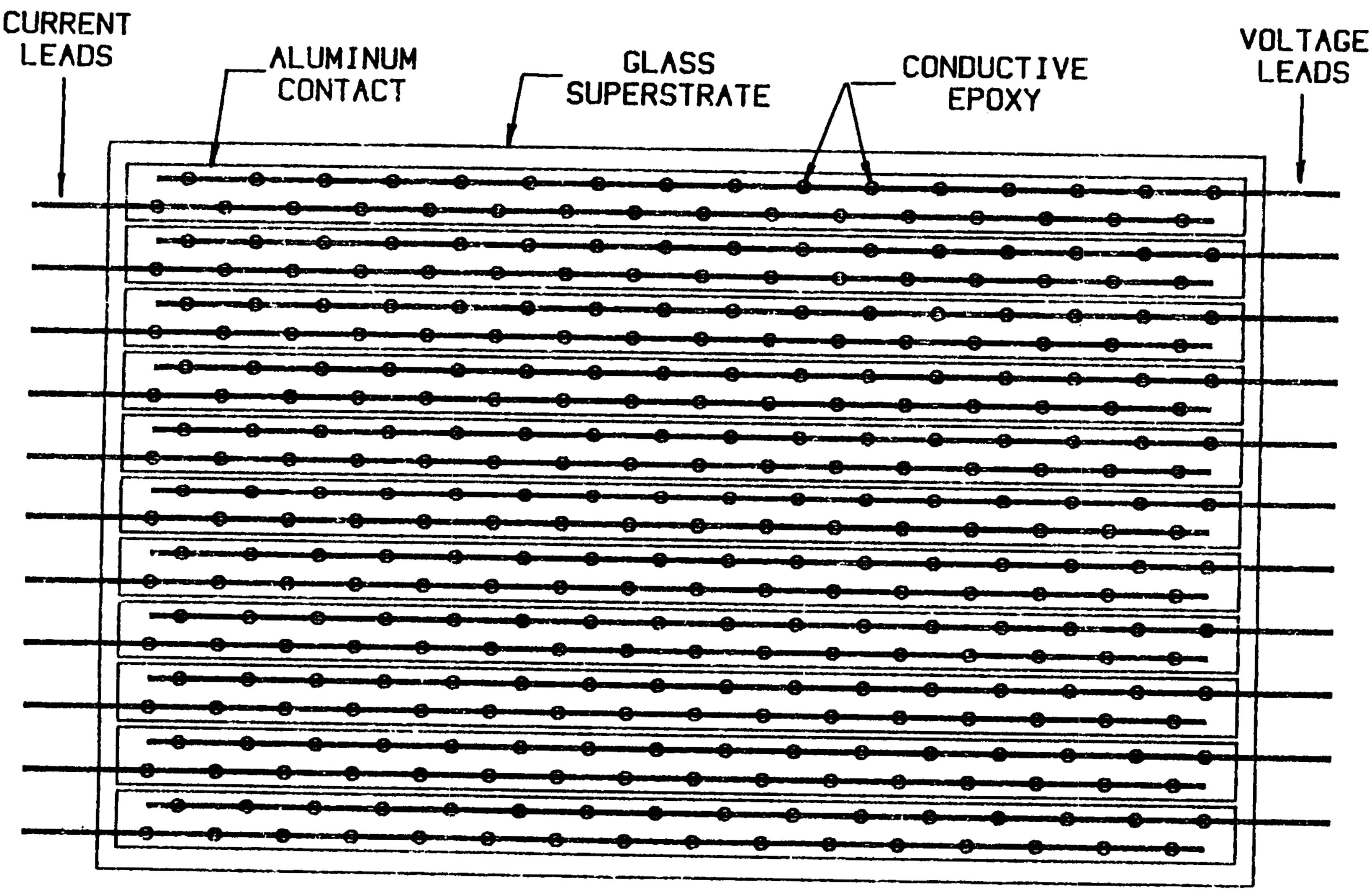


Figure 3. Bottom view of Module Showing Epoxy Lead Attachment

was encountered with the cured epoxy contacts removing the silicon film from the glass substrate at low or zero stress levels. It was felt that this lack of adherence between the deposited film and glass indicated the lack of proper substrate cleaning on the part of the manufacturer prior to deposition. None of the other cells exhibited this effect.

Electrical measurement of the individual cells in a monolithic module was performed by exposure to an ELH simulator for approximately 1 second. During the exposure of each cell, adjacent cells were masked to avoid the possible cumulative effects of light induced defects. The mask was not able to prevent exposure of the parasitic cell shown in Figure 2, however. A stable simulated reference cell made from filtered silicon diodes was used to initialize the simulator illumination. When used with ELH illumination, this simulated reference cell has been shown to result in measurement repeatability to within 1% (12). Temperature was monitored by a platinum resistance thermometer and controlled to 25 $\pm$ 1 C during measurement by the flow of conditioned air.

After measurement the monolithic module was placed in an oven at an elevated temperature for a given length of time. At the end of this time the oven was turned off and the module allowed to cool to room temperature with the door open. After cooling, the module was withdrawn and remeasured. The process was repeated a number of times in such a way that cumulative stress time doubled prior to each measurement. Initially, measurements were made after cumulative times of 20, 40, 80, 160, ... hours, but because effects were being observed at shorter times, this was changed to cumulative times of 2.5, 5, 10, 20, 40, ... hours. Times less than 2.5 hours are not practical because of thermal rise and fall times associated with the oven and because of the background stress associated with curing the epoxy contacts.

Because exposure to light is known to induce electrical change in amorphous silicon cells (15), it is necessary to carefully control the amount of exposure given to each module under test. The complete stress plan for amorphous cells is shown in Figure 4. The simplest form of stress involves elevated temperature without light exposure. In this procedure modules are kept in the dark except for the 1 second exposure during measurement. Since no net current flows when the cell is in the dark, the loading of non-illumunated cells should not make a difference, but tests to confirm this were run using both open circuited and short circuited cells. However, in order to see if exposure to light, and the resulting current flow through the cell, would make a difference in long term degradation effects, modules were also exposed to light while at elevated temperatures. This was accomplished by exposing multiple cell modules, with alternate cells either shorted or open, to approximate 1-sun illumination through a transparent oven door. Ultimately it would also be desirable to stress cells held at constant voltage to simulate their behavior during battery charging applications. While this condition is included in Figure 4, time did not permit this type of testing to be performed. Since light induced defects can be removed by annealing, test procedures called for immediate measurement followed by a 2.5 hour anneal at 100 C in the dark, followed in turn by the final measurement. A comparison of the two post-stress measurements could be used to indicate the presence of non-permanent light induced defects introduced during stressing. In addition, measurements were made on two control cells, one of which was kept in the dark at 25 C and one of which was kept in the light at 30 C, the additional 5 degrees being due to the heating effect of the illumination.

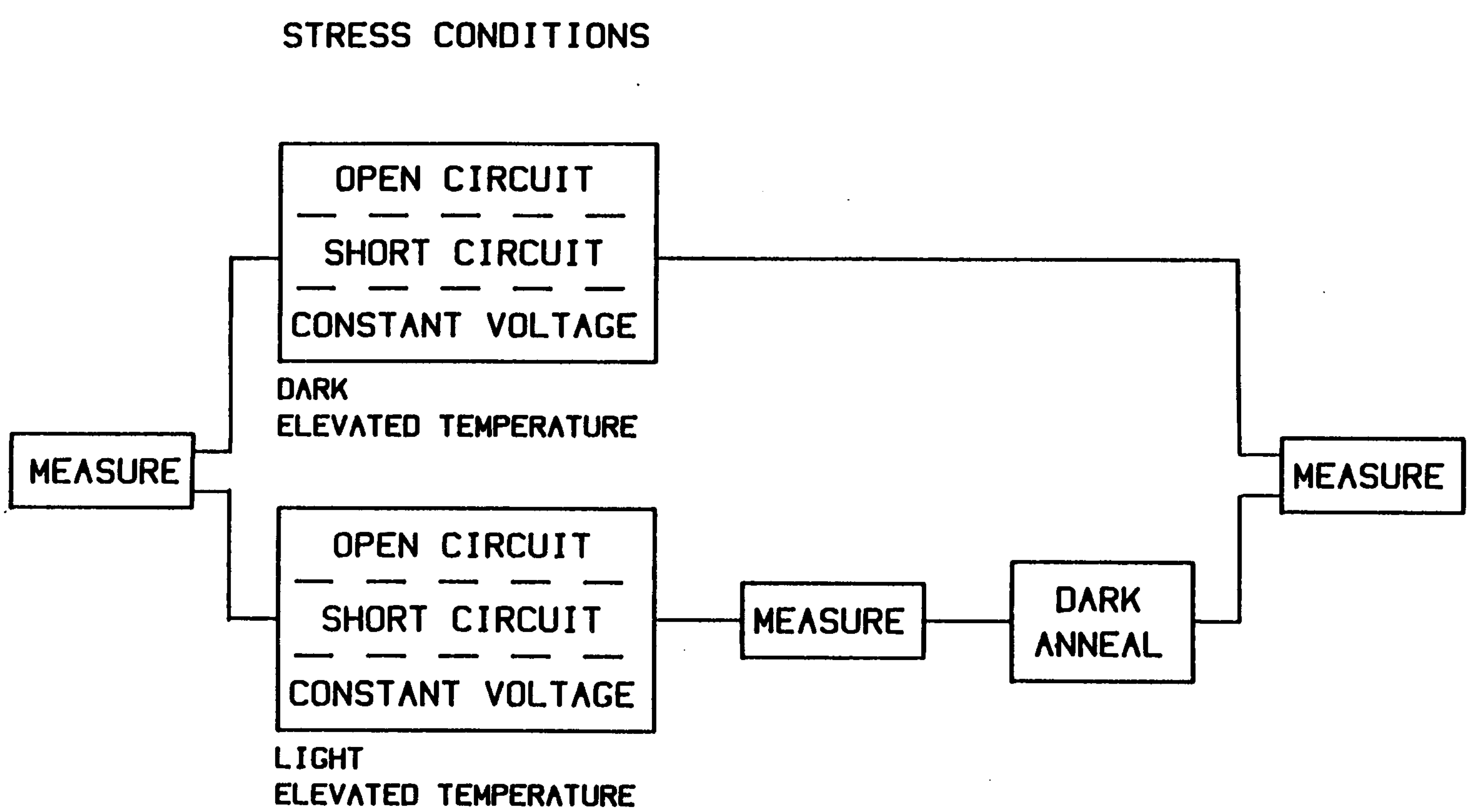


Figure 4. Stress Plan for Thin Film Amorphous Silicon Cells

In addition to the schedule shown in Figure 4, step stress tests were conducted on the different type modules in an effort to find the maximum stress temperature that could be used without introducing extraneous failure modes (10). In all the single junction cells tested an abrupt transition was noted between 150 and 160 C so that a maximum stress temperature of 140 C was selected. On the one type of tandem cell type tested no transition was noted even as high as 200 C and 180 C was selected for this type.

3.0 AMORPHOUS CELL ACCELERATED TEST RESULTS

Unencapsulated samples, consisting of up to 16 individually addressable, single junction, cells on a common glass superstrate, were obtained from three manufacturers. These were assigned arbitrary single letter identifications, "A" through "E", based on the chronology of their receipt. Cells "A" and "C" were obtained from one manufacturer, "B" and "D" from a second manufacturer, and "E" from a third. As discussed in the previous section, Cell type "D" could not be stress tested because of lack of adhesion between films and glass superstrate.

Pre-stress electrical characterization of many of the multiple cell modules indicated that a wide variation in Voc from cell to cell. Voc populations tended to be bimodal, with "high Voc" cells centered about 0.8 volts, "low Voc" cells centered about 0.3 volts, and with relatively few cells falling between the two peaks. Some modules had all, or nearly all, high Voc cells, while others had about a 50-50 split between the two types. It was rare to find modules which had a majority of low Voc cells, presumably because such modules would have been rejected by the manufacturer (even for reliability studies!). The high Voc cells had relatively rectangular IV characteristics while the low Voc cells exhibited poor fill factors and rounded IV characteristics normally associated with low shunt resistances.

The first elevated temperature stress tests were performed at 140 C in the dark on a cell type "A" module consisting of 8 low Voc and 4 high Voc cells on a common substrate. Results of measuring Pm, Voc, and Isc are shown in Figures 5,6, and 7 respectively. It can be seen that in general there was initial improvement in Voc followed by irreversible degradation, with corresponding improvement and degradation in the maximum power output, Pm. As would be expected, low Voc cells showed a much greater initial increase due to stress than high Voc cells, since the high Voc cells were already near their maximum possible value. The improvement in Voc for initially low Voc cells was dramatic, going from an average of 0.28 volts to 0.8 volts with most of that increase occurring within the first 20 hours of stress. The short circuit current, however, showed relatively little change -- a slight increase in the first 40 hours for cells with low Voc followed by a gradual decline. Only the low Voc cells are shown in Figure 7 because, except for the slight initial improvement, there was no difference between the two types. The dramatic improvement in Pm is thus obviously related to changes in Voc rather than Isc. Appreciable irreversible degradation in Pm was observed after about 1000 hours for both high and low Voc categories. The test was terminated after 2560 hours. At this point Voc and Isc on the average had both declined moderately, while Pm was about 50% of its maximum value.

It is important to remember that the curves plotted in Figures 5, 6, and 7 are averages and it is possible within these averages to have rather wide individual variations. Figures 8, 9, 10, and 11 are VI characteristic curves for the 4 high Voc cells (A, F, J, and N), taken initially and after 2560 hours. Cell A showed relatively little change while the others indicated various amounts of increased diode leakage resulting in decreased shunt resistance and decreased fill factor. Figure 12 shows VI characteristics of a typical low Voc cell (D) on the same module initially and after 80 and 2560 hours. The 80 hour intermediate time was chosen because it represented the

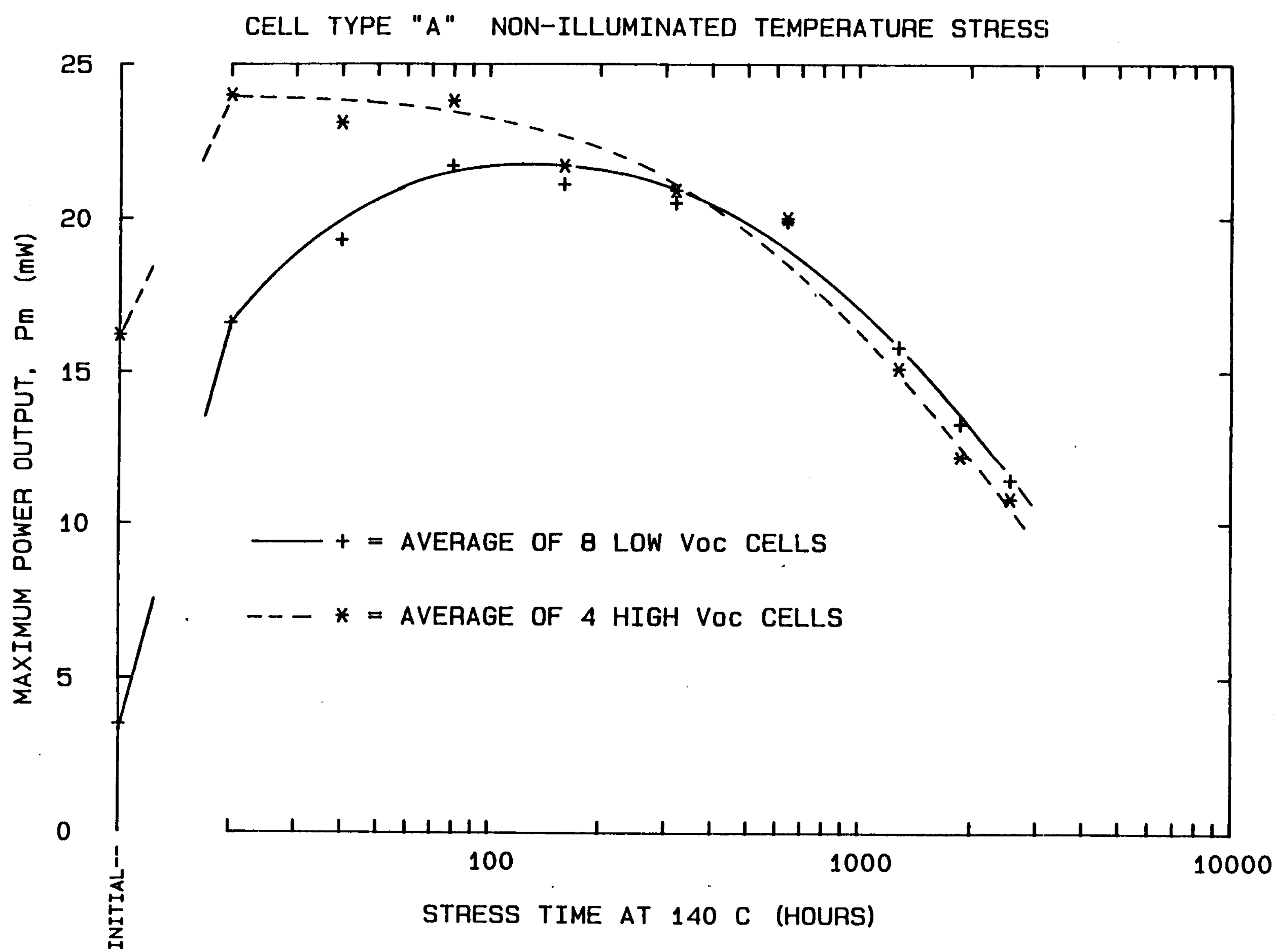


Figure 5. Pm vs Non-illuminated 140 C Stress Time for Type "A" Module

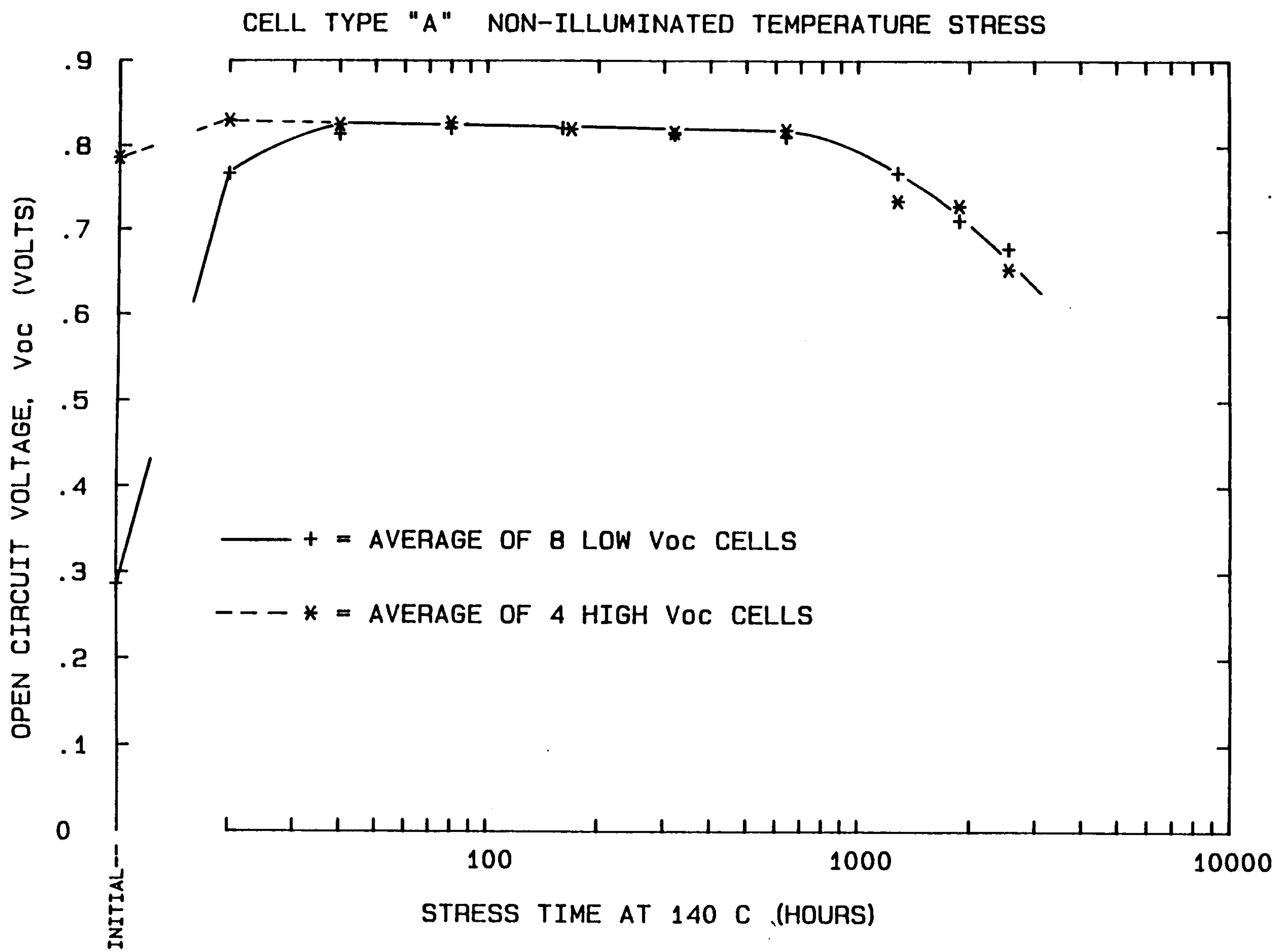


Figure 6. Voc vs Non-illuminated 140 C Stress Time for Type "A" Module

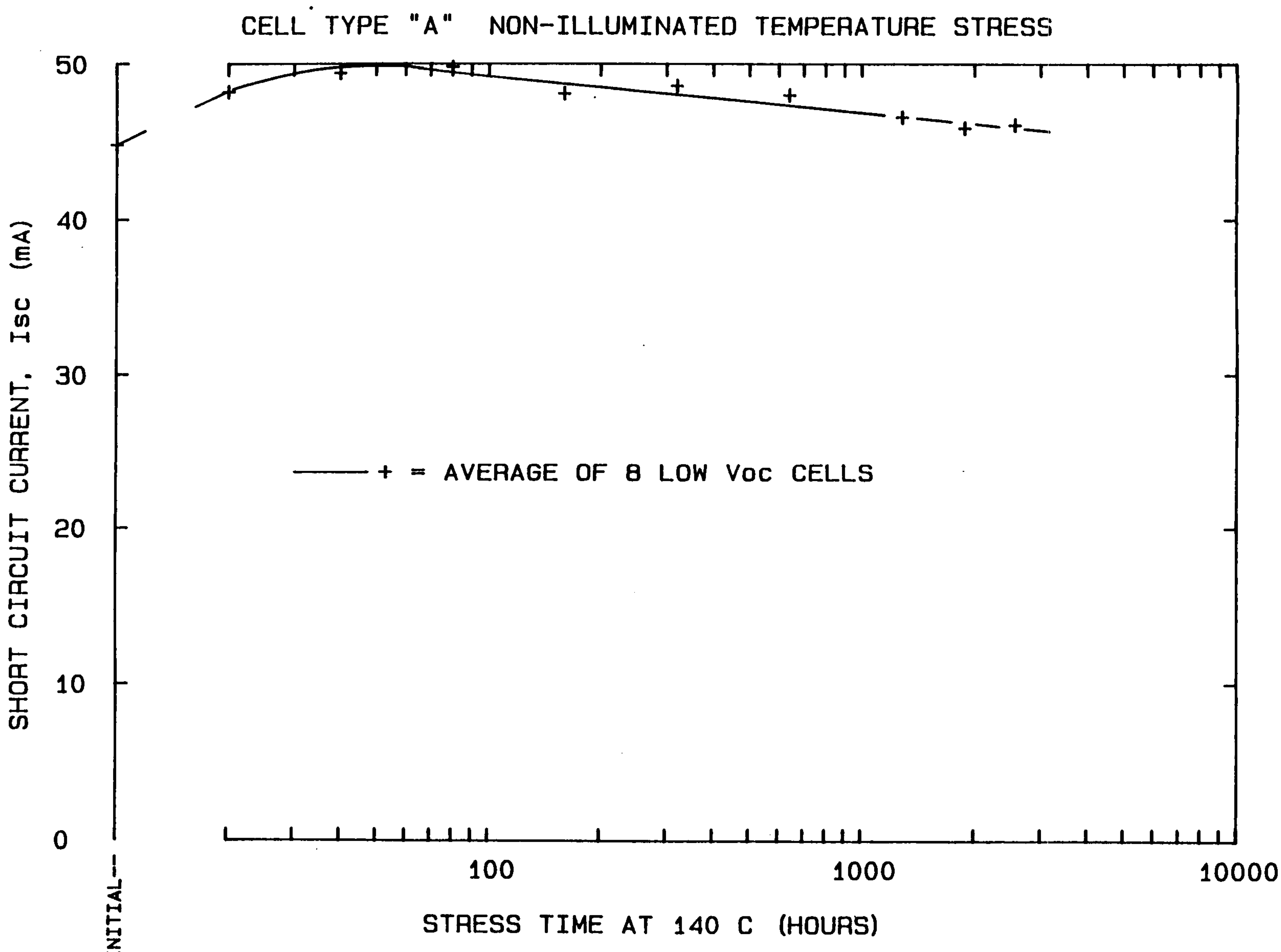


Figure 7. Isc vs Non-illuminated 140 C Stress Time for Type "A" Module

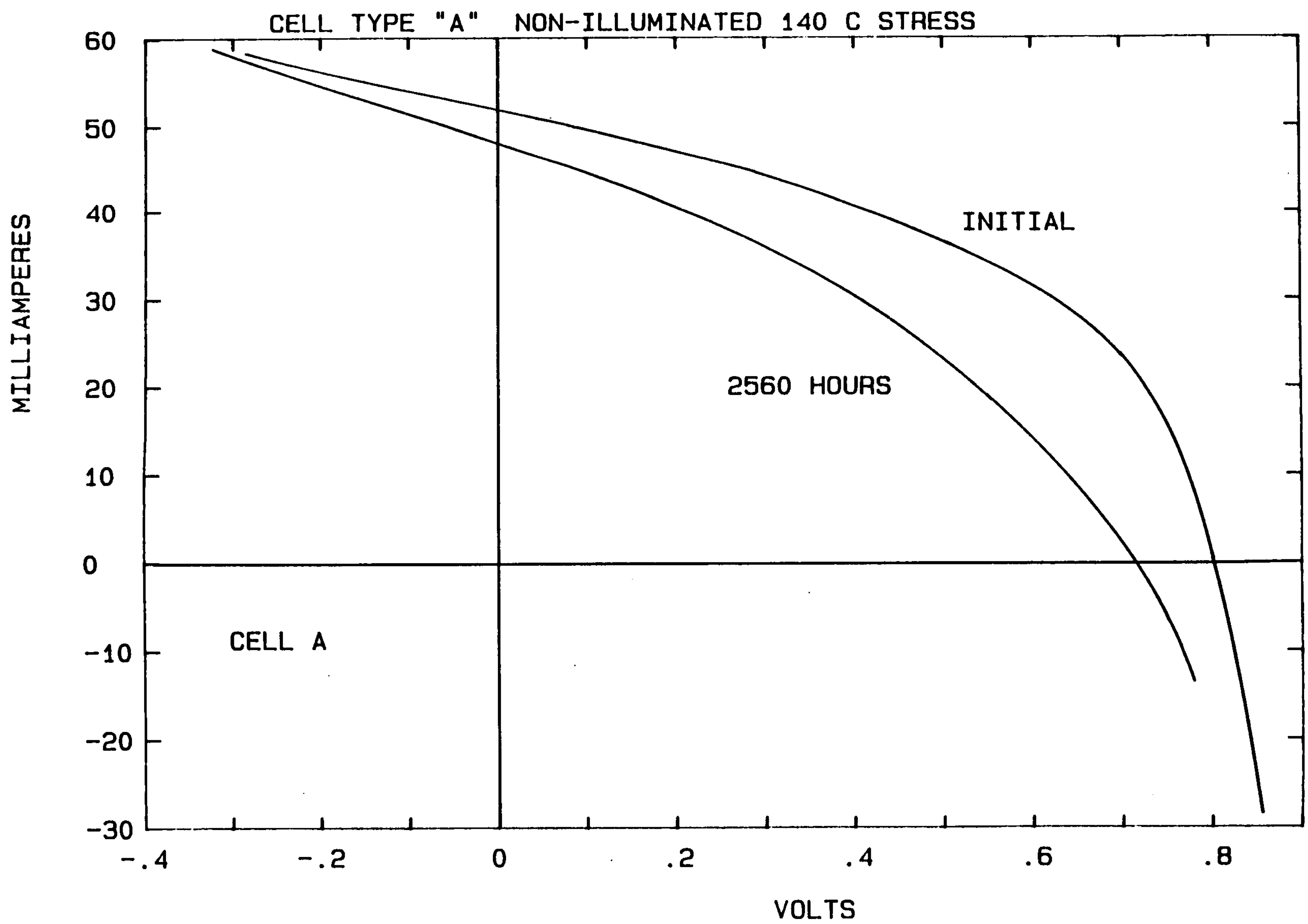


Figure 8. VI Characteristics for Cell A (high Voc) from Type "A" Module

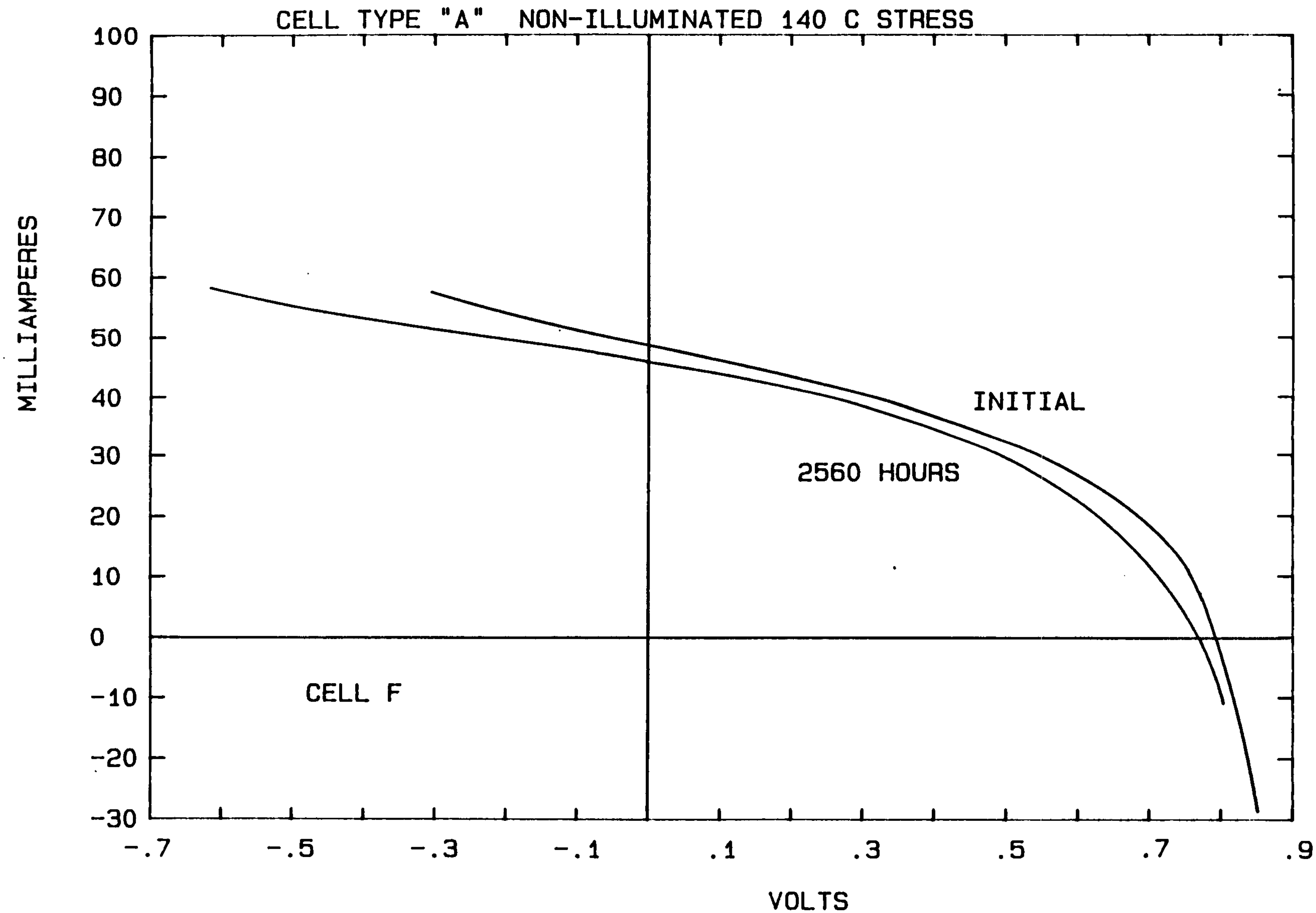


Figure 9. VI Characteristics for Cell F (high Voc) from Type "A" Module

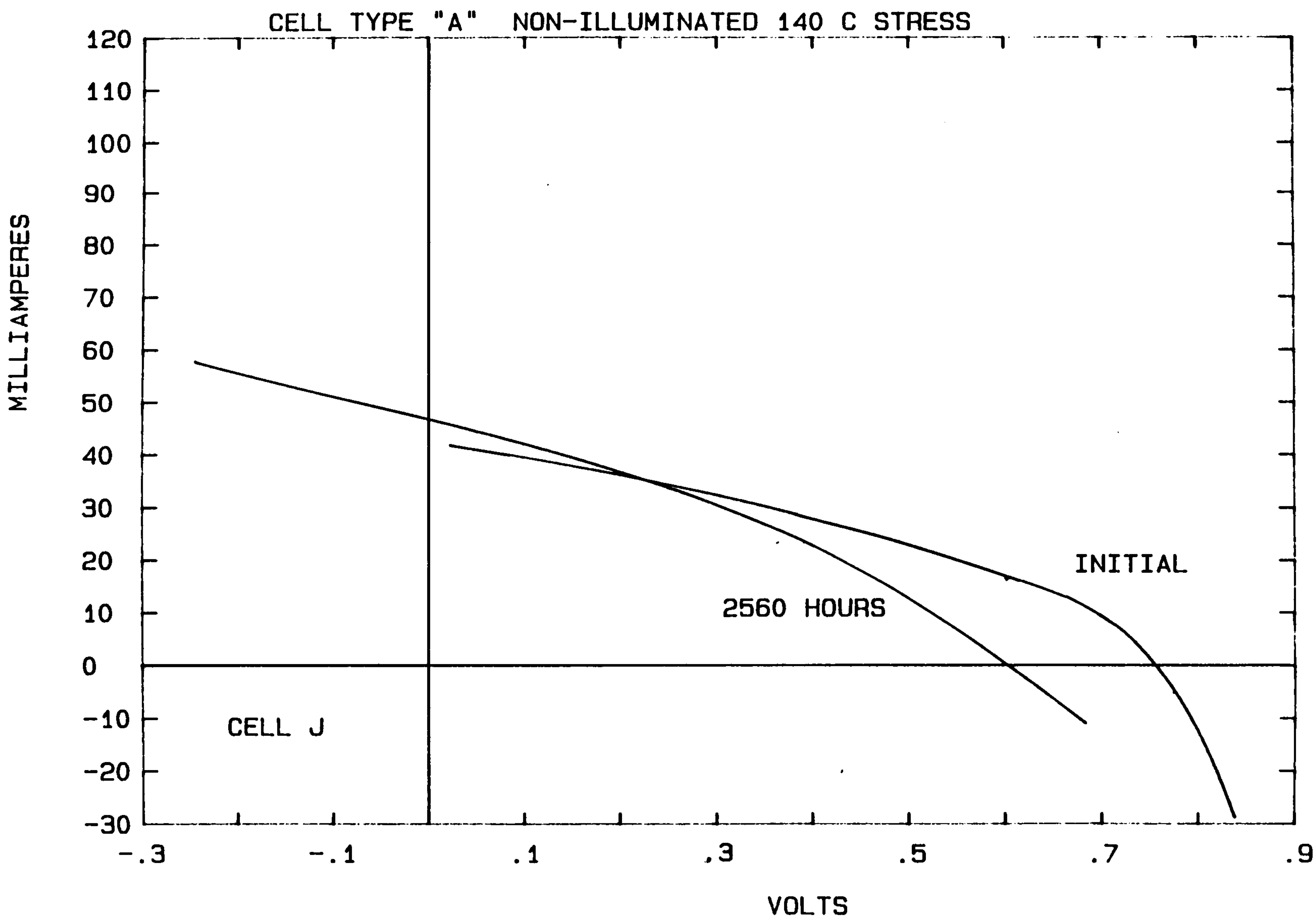


Figure 10. VI Characteristics for Cell J (high Voc) from Type "A" Module

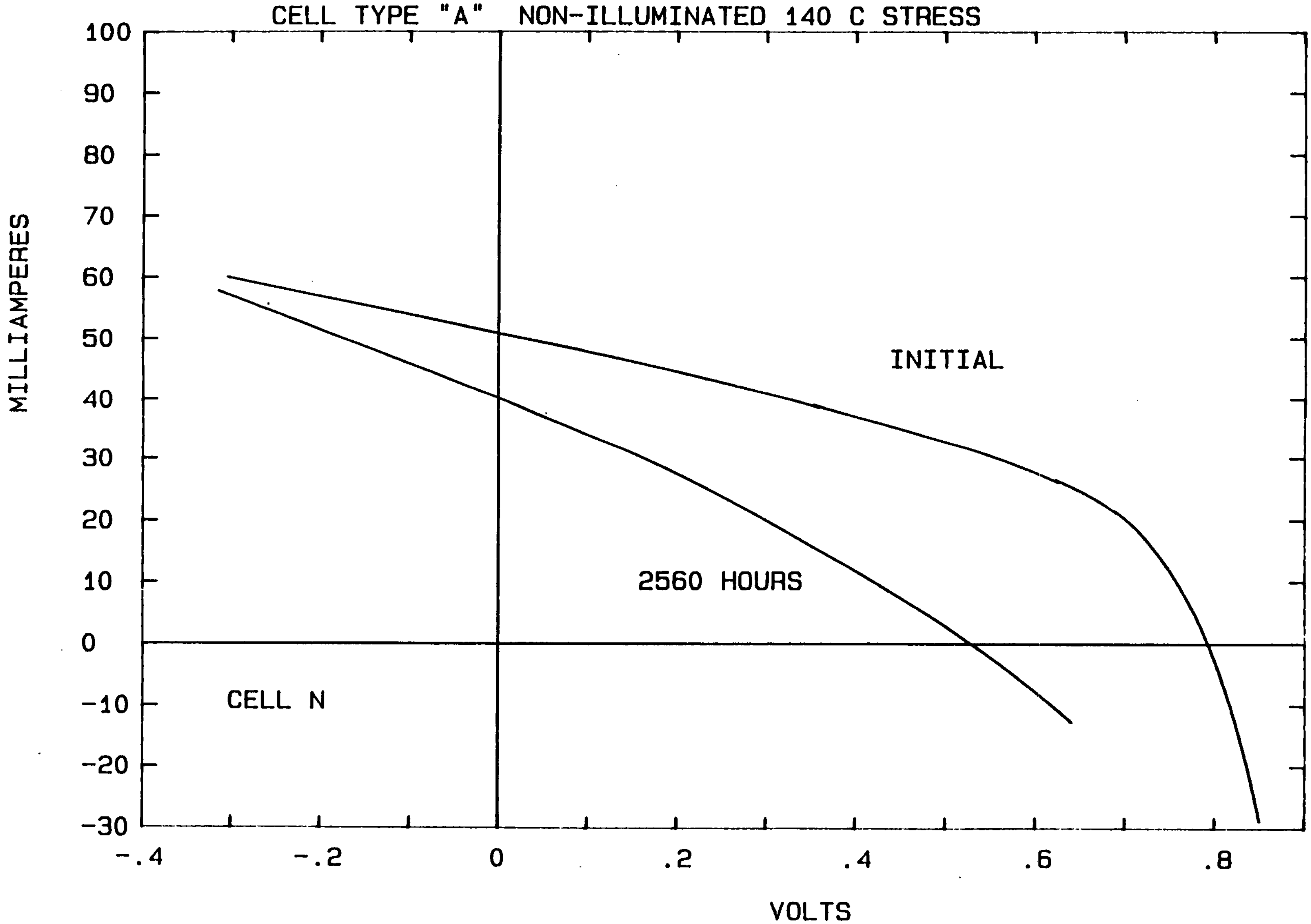


Figure 11. VI Characteristics for Cell N (high Voc) from Type "A" Module

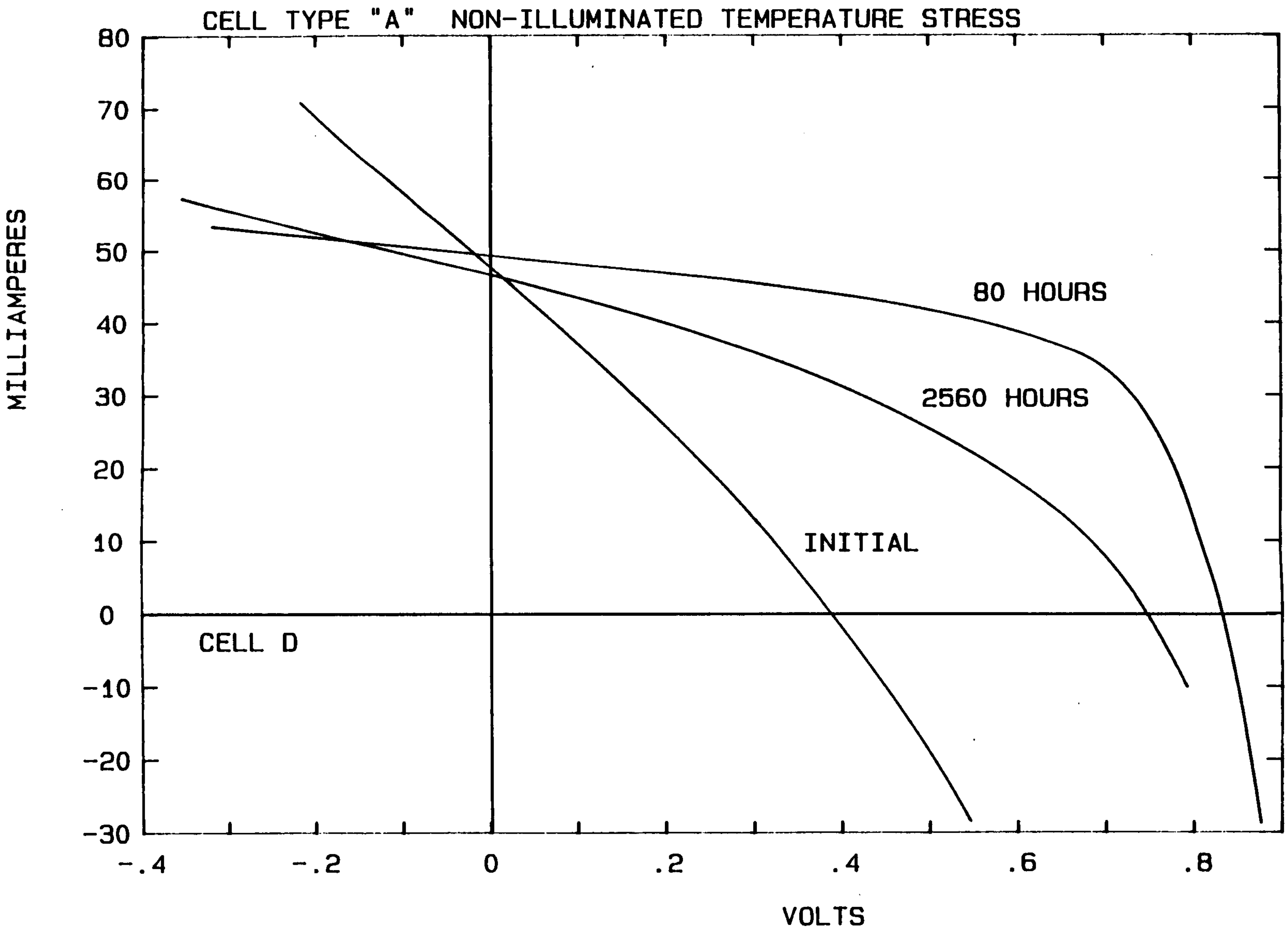


Figure 12. VI Characteristics for Cell D (low Voc) from Type "A" Module

point of maximum improvement. The change in the characteristic is quite dramatic and is due almost entirely to a reduction in cell leakage which results in increased shunt resistance.

Having observed the initial rapid improvement of module "A" it was determined that the next test should start with a stress time of 2.5 hours instead of 20 hours. Consequently a "B" module consisting of 7 high Voc cells and 6 low Voc cells on a common substrate was subjected to 140 C stress testing in the dark . Results of these tests are shown in Figures 13, 14, and 15 for Pm, Voc, and Isc respectively. This module was made by a different process and by a different manufacturer from that of module "A" and did not show initial improvement even though Voc values were initially lower than normal. Its degradation was much more rapid than that of module "A", decreasing to 50% of initial power after only 30 hours. Color changes were evident to the eye and large decreases in both Voc and Isc were measured. This seems to imply that the module was poorly made in some fundamental sense and it is possible that this defective condition is the reason no initial improvement was noted. Under normal manufacturing conditions this module would undoubtably have been considered a reject.

The next module to be stressed was type "C", which was a later version of type "A". The type "C" module was subjected to both light and dark elevated temperature stressing. The module consisted of 16 cells of which one half were shorted during stress and one half left open. Figures 16, 17, and 18 summarize the results of stressing at 140 C in the dark on Pm, Voc, and Isc respectively. This module was quite uniform with all cells having high Voc values and hence only a very slight initial improvement was noted,. However

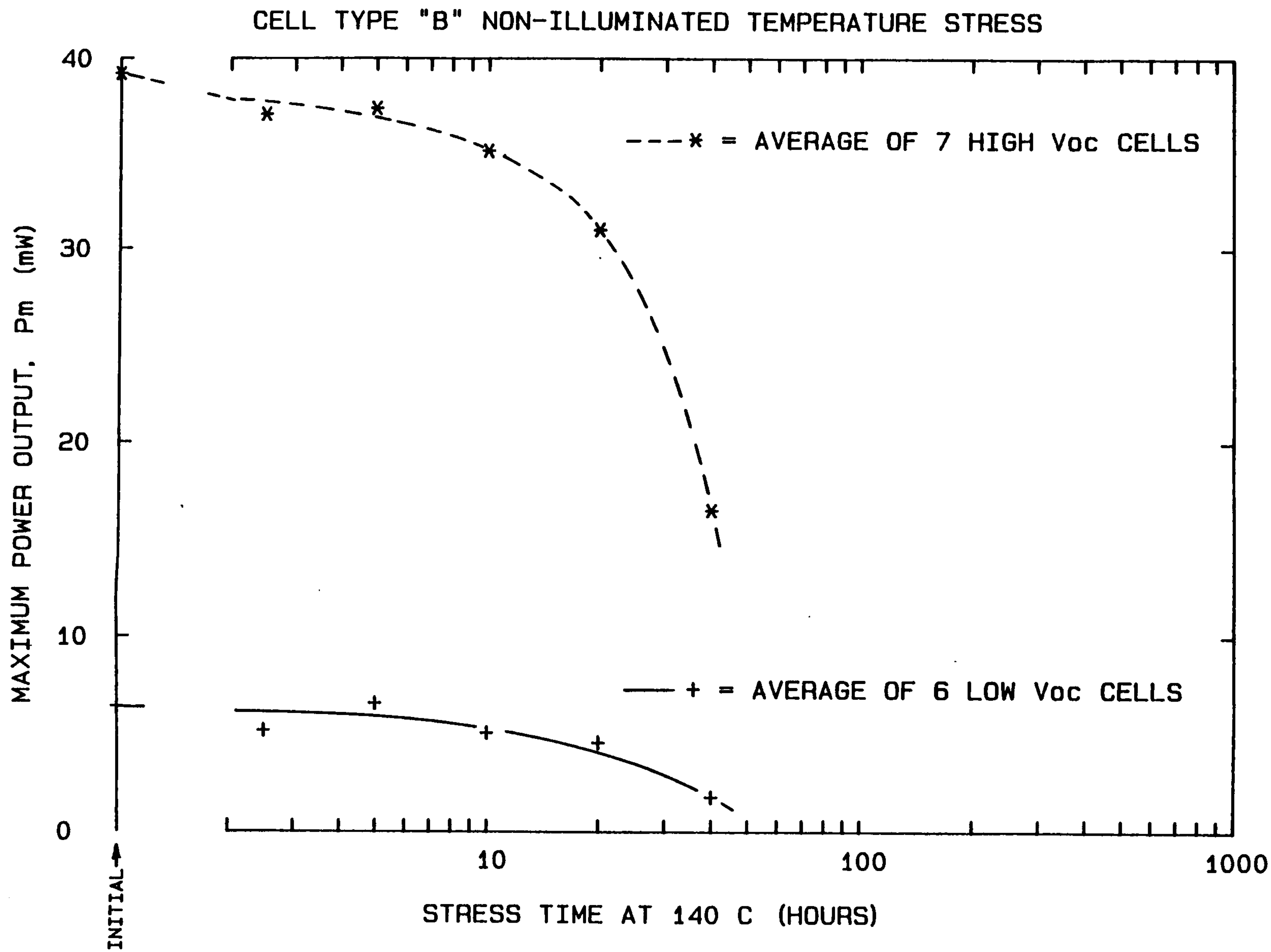


Figure 13. Pm vs Non-illuminated 140 C Stress Time for Type "B" Module

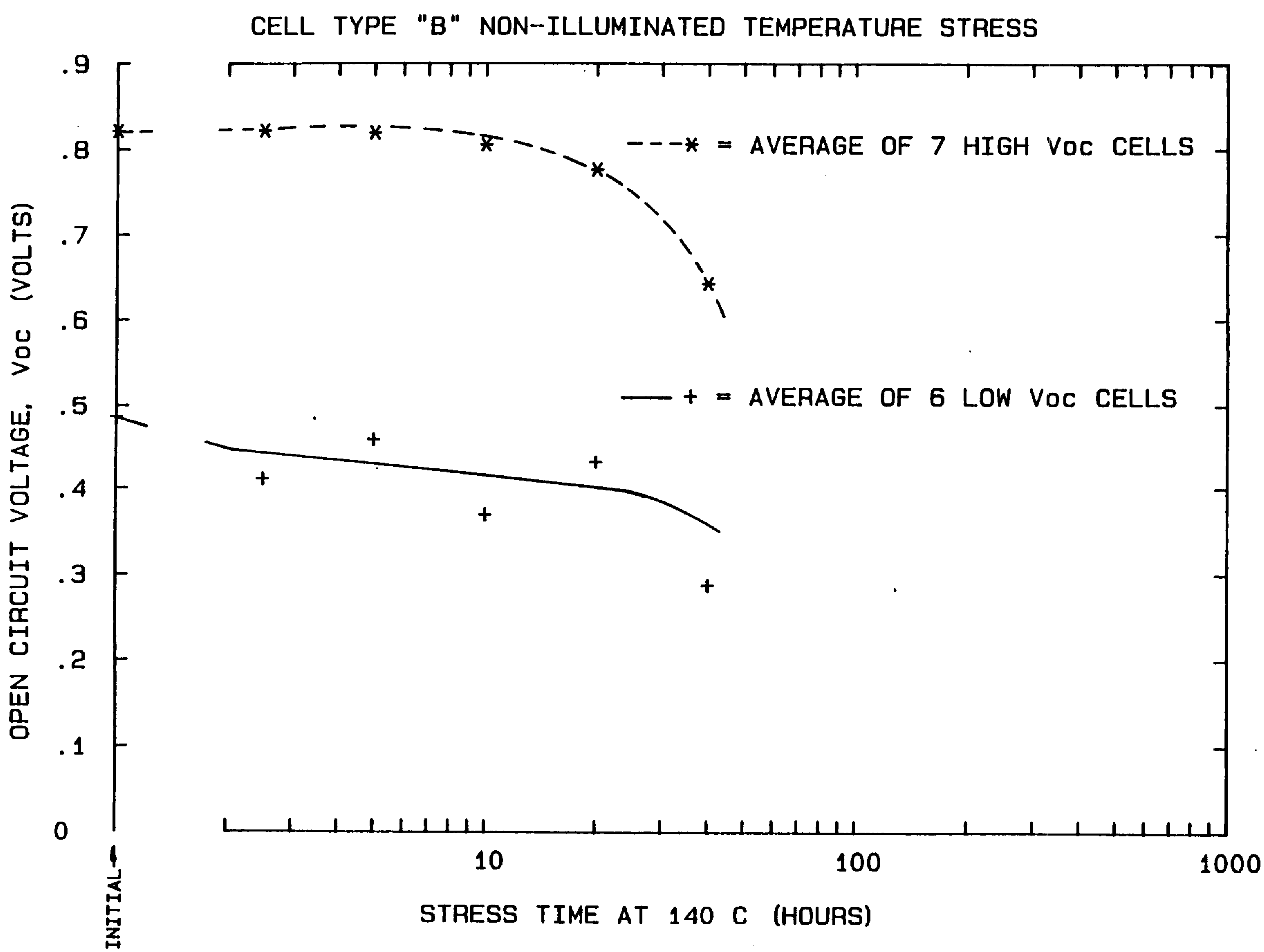


Figure 14. Voc vs Non-illuminated 140 C Stress Time for Type "B" Module

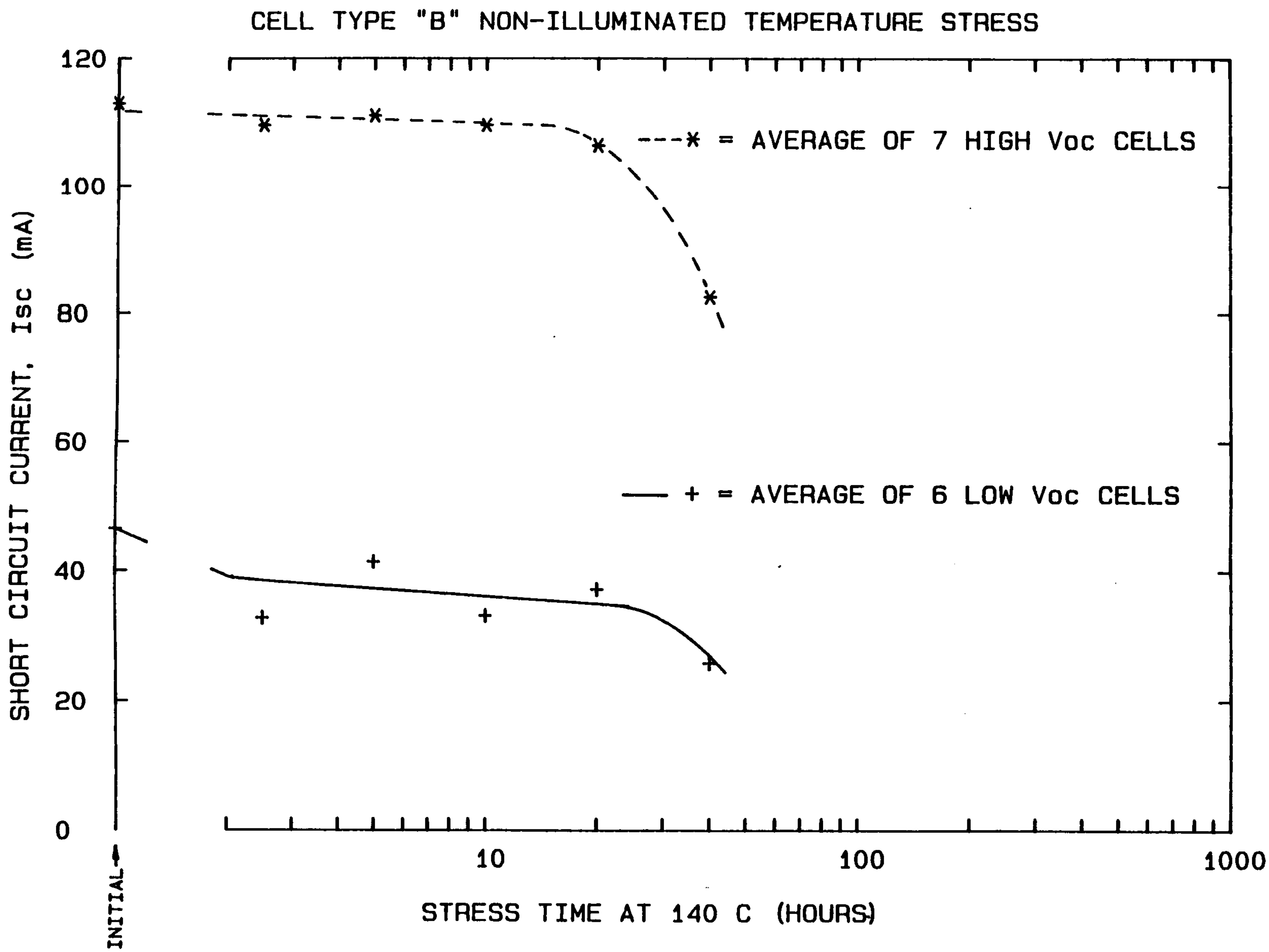


Figure 15. Isc vs Non-illuminated 140 C Stress Time for Type "B" Module

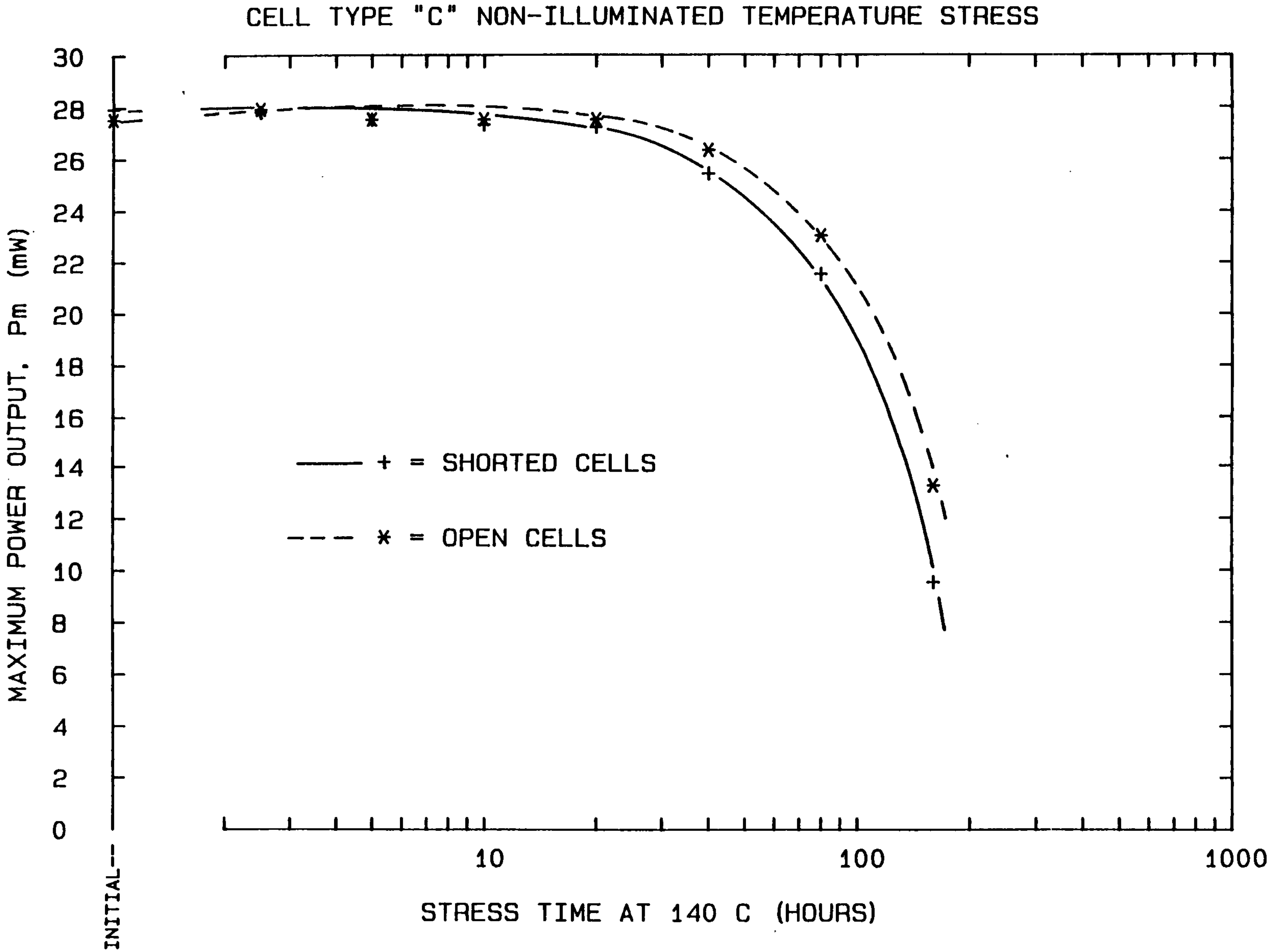


Figure 16. Pm vs Non-illuminated 140 C Stress Time for Type "C" Module

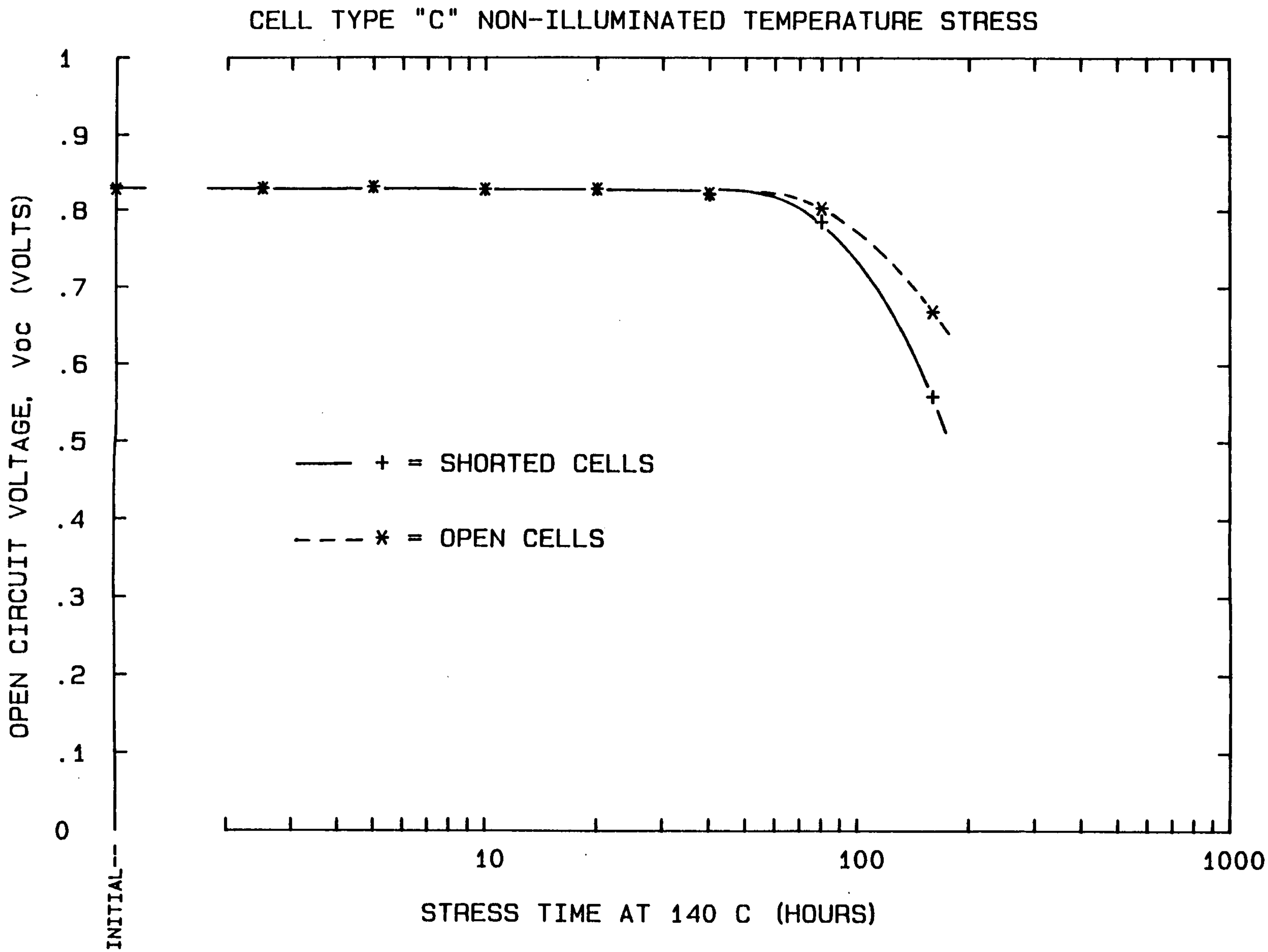


Figure 17. Voc vs Non-illuminated 140 C Stress Time for Type "C" Module

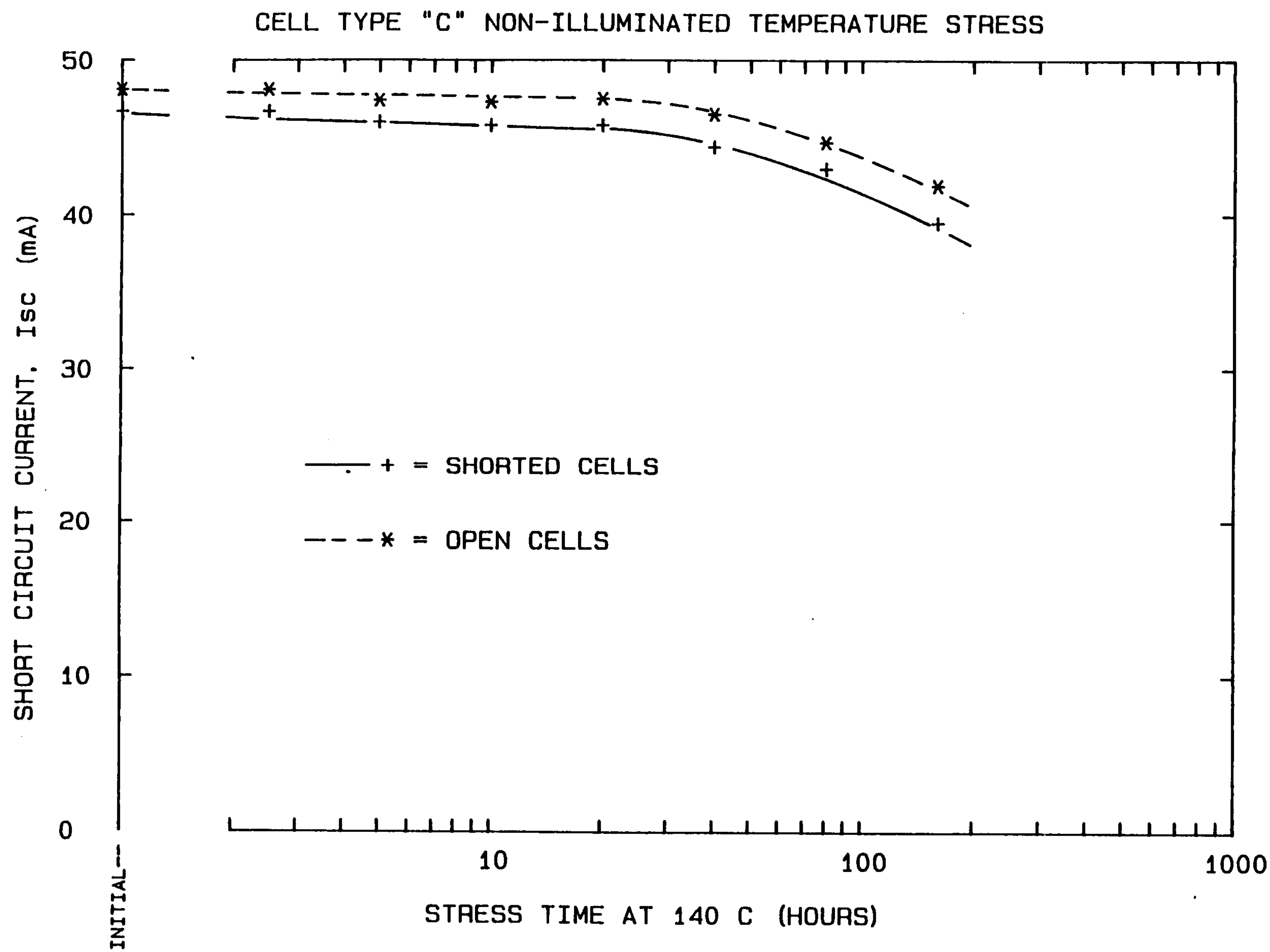


Figure 18. Isc vs Non-illuminated 140 C Stress Time for Type "C" Module

irreversible degradation was observed after a relatively short time with a 50% reduction in Pm noted after only 150 hours, an order of magnitude earlier than for Cell Type "A". It was as if process improvements put in place by the manufacturer had corrected one problem -- the wide distribution of initial Voc values -- only to create another that resulted in much shorted accelerated life. As a matter of fact, the degradation characteristics of this module looked very much like those of module "B". No difference could be observed in the behavior of Isc between open circuited cells and shorted cells. Some difference in Voc was observed after 80 hours and there was a small, but consistent difference in Pm, with the shorted cells always showing more degradation at a given stress level than open cells. There appears to be no obvious physical explanation for this effect and it is thought to be an artifact of the small statistical sample. To illustrate measurement repeatability the average value of Isc for a 16 cell control module is shown in Figure 19. It can be seen that Isc varies less than 1%.

Figures 20, 21, and 22 summarize the results of subjecting a "C" module to 140 C illuminated stress on Pm, Voc, and Isc respectively. This module contained populations of both high and low Voc cells and these are broken out for the Voc and Pm plots. The shorted group contained 2 low Voc cells and 6 high, while the open group contained 3 low Voc cells and 5 high. These numbers are insufficient for meaningful statistics, but might serve to indicate gross effects if present. The Isc plot was not broken out by high and low Voc cells since there was little difference between the two categories for this parameter. It is difficult from the data to spot clear trends with regard to the 2.5 hour 100 C anneal cycle, but it does appear in many cases that the effect of the anneal is to reduce the parameter value (Pm, Isc, Voc). This

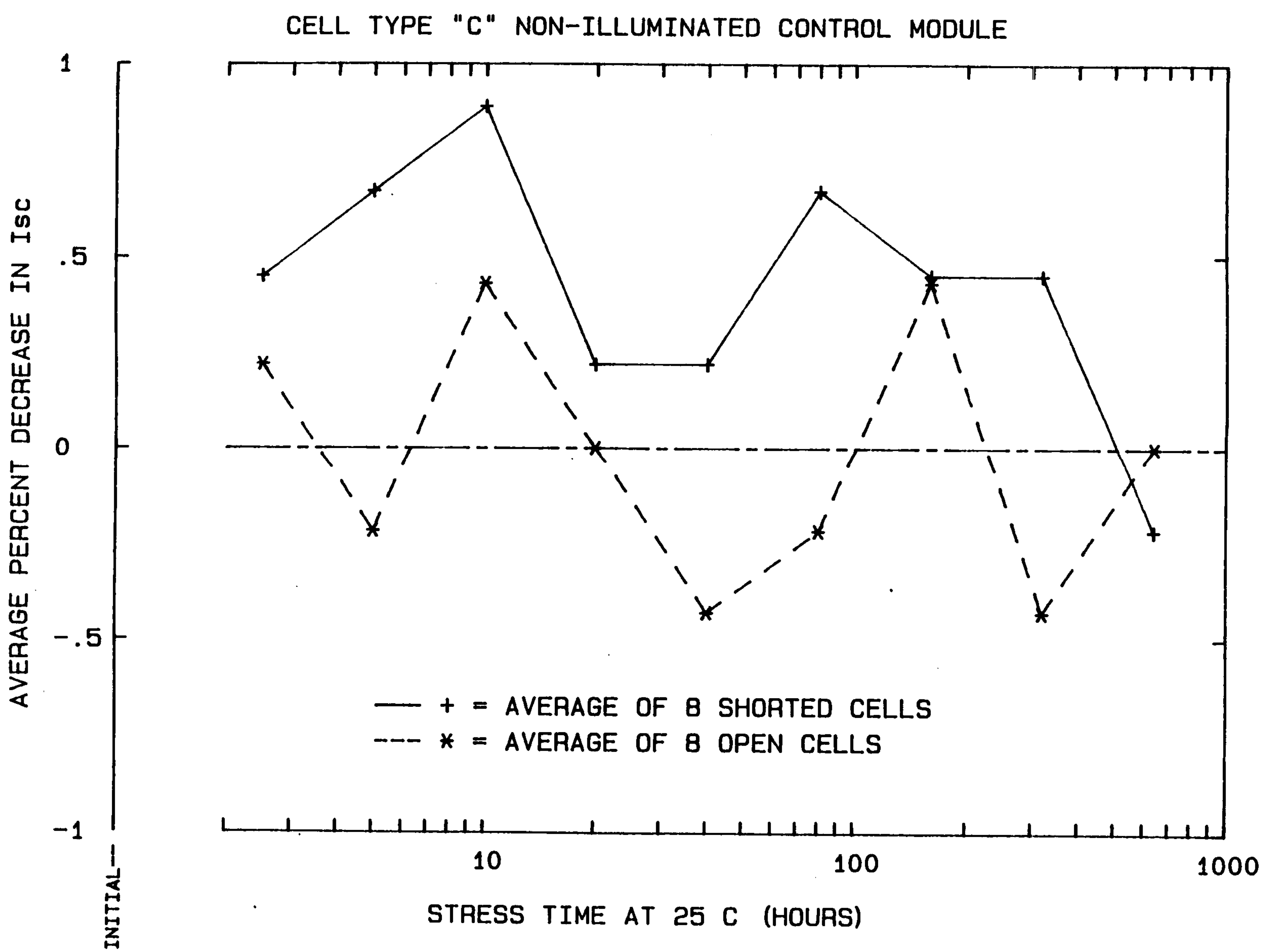


Figure 19. Percent Decrease in Isc for Non-illuminated Type "C" Control Module Held at 25 C

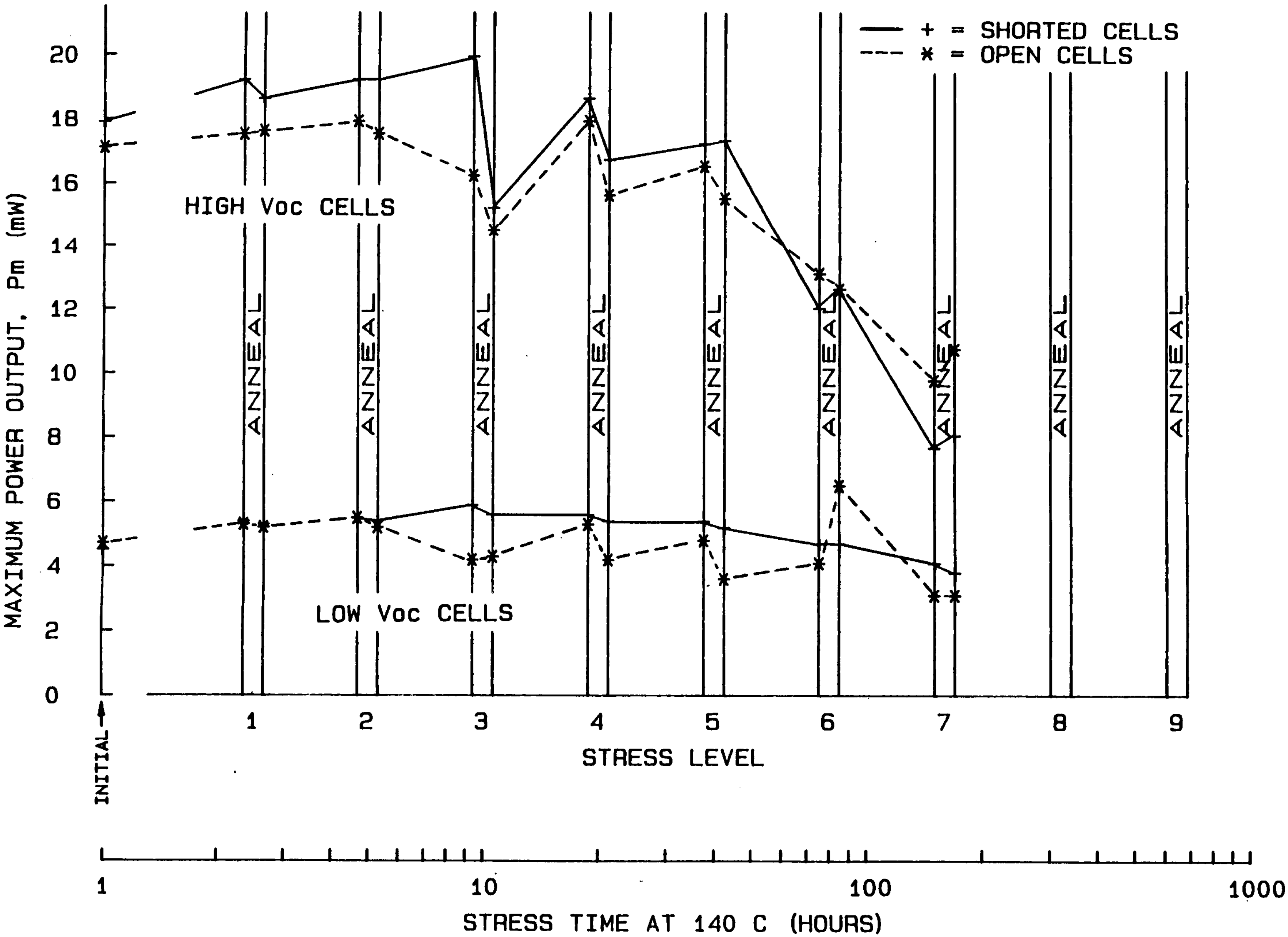


Figure 20. Pm vs Illuminated 140 C Stress Time for Type "C" Module

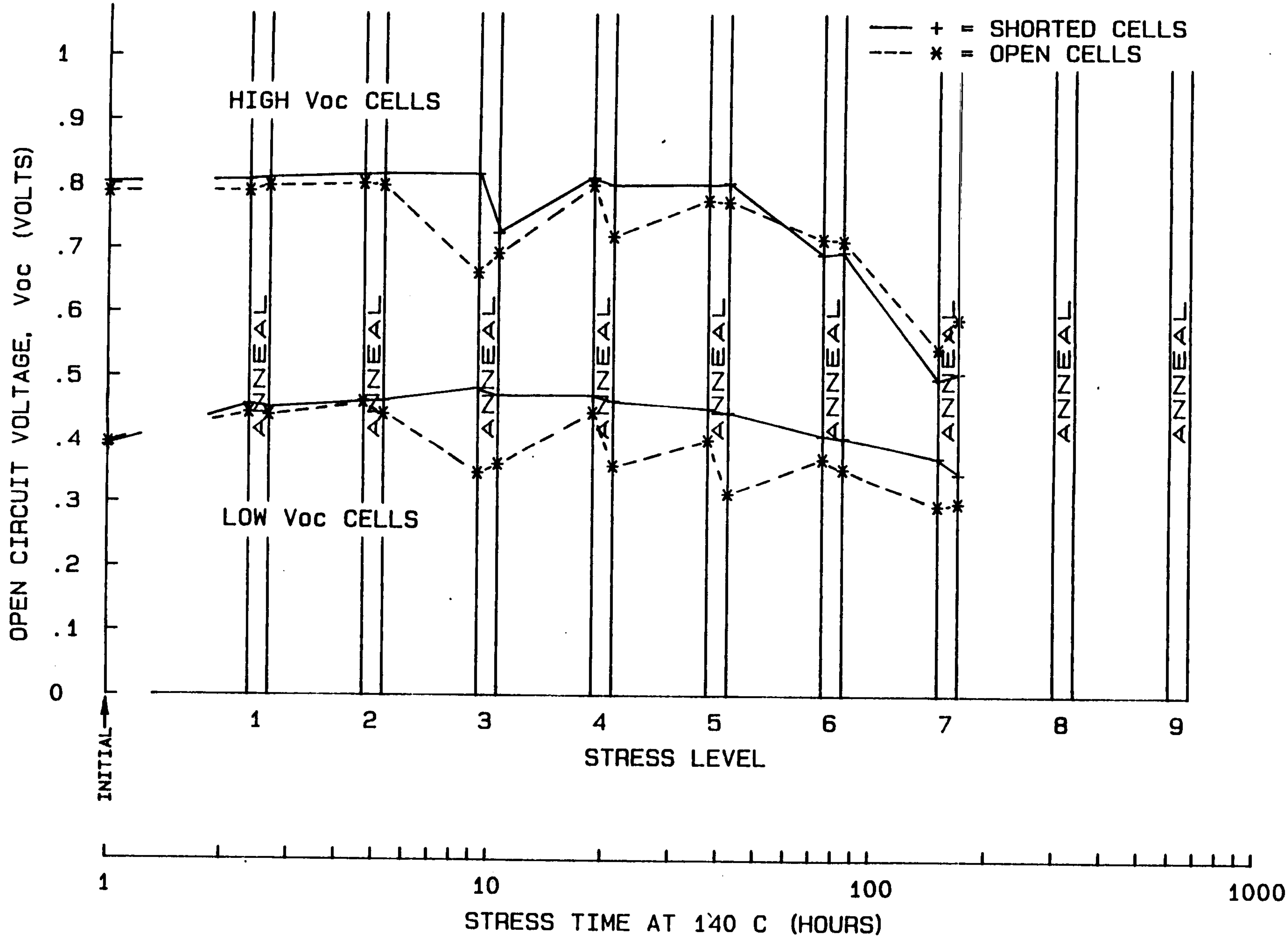


Figure 21. Voc vs Illuminated 140 C Stress Time for Type "C" Module

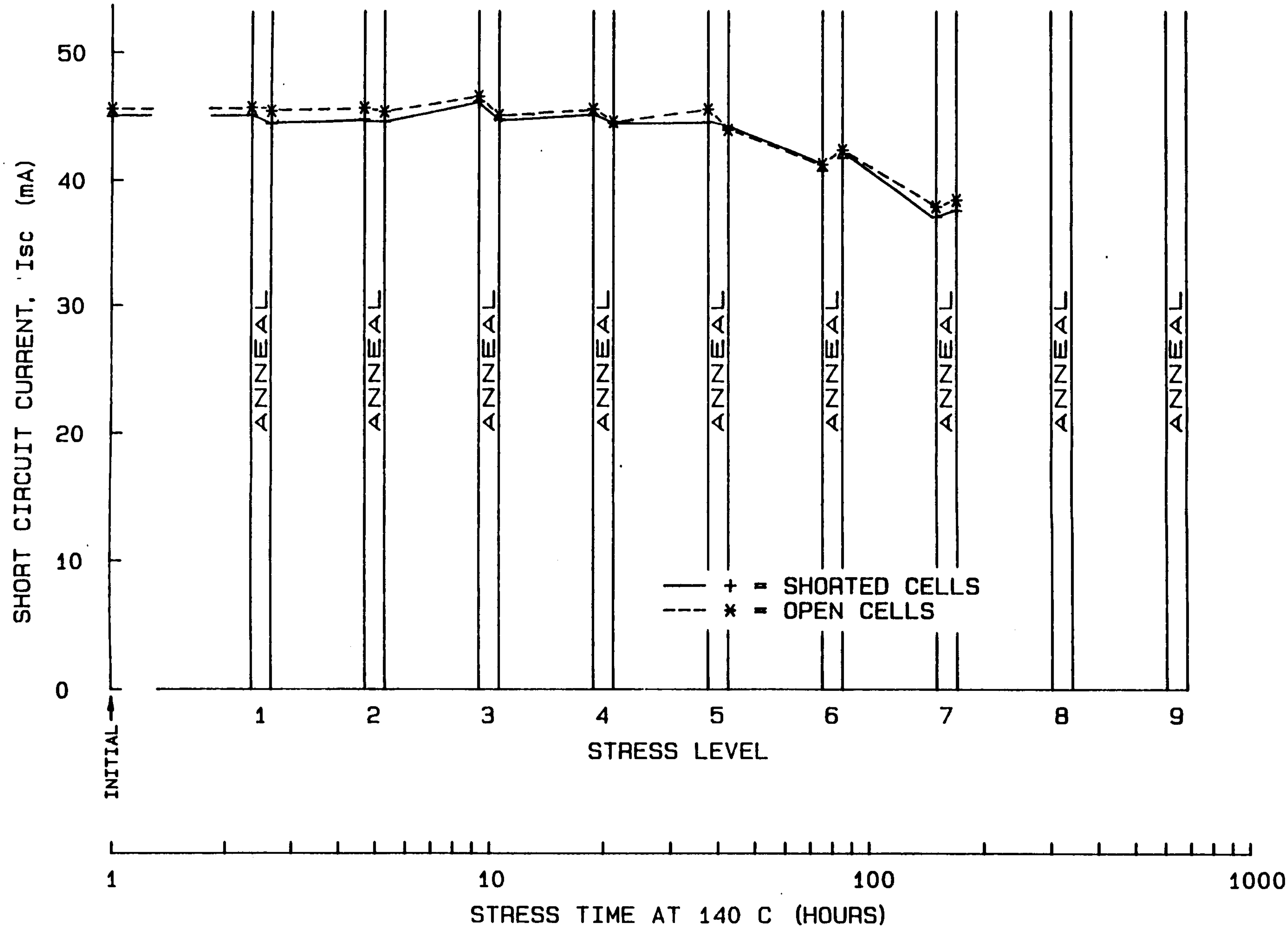


Figure 22. Isc vs Illuminated 140 C Stress Time for Type "C" Module

trend is shown in Figure 23 for Isc where it is shown that of the 7 anneal cycles used during illuminated stress testing of the "C" module, 5 resulted in reducing Isc from its pre-anneal value. This is opposite to conventional thinking which would be that light induced effects cause a reduction in Isc or Pm, with a subsequent anneal returning the parameter to more or less its original value (16). An "inverse" Staebler-Wronski effect has been reported at high illumination levels (17), but this is the first indication of such behavior with respect to temperature stress. Clearly the effect of illumination at high temperature is different from that reported in the literature at room temperature.

To see if "C" cells held at room temperature rather than 140 C behaved in the expected fashion, a control module was illuminated with the results shown in Figure 24. Light induced Staebler-Wronski type degradation, and subsequent recovery during the 100 C anneal, is clearly evident in the open circuited light-exposed control cell and to a much lesser extent in the short circuited cells. Thus it appears that the cells do indeed show the classic behavior at room temperature. It appears that the effect of high temperature stress is opposed to light induced degradation, but in so doing introduces a fair amount of variability. Increased degradation resulting from the 100 C anneal is clearly unexpected.

A comparison of the hign Voc "C" module subjected to 140 C stress testing in the dark with the high Voc "C" cells on the light stressed modules shows very similar behavior despite the variability of the light stressed cells. In Figure 25 normalized average values of Pm are shown for all high Voc cells of both the light stressed and dark stressed modules (superposition of Figures 16

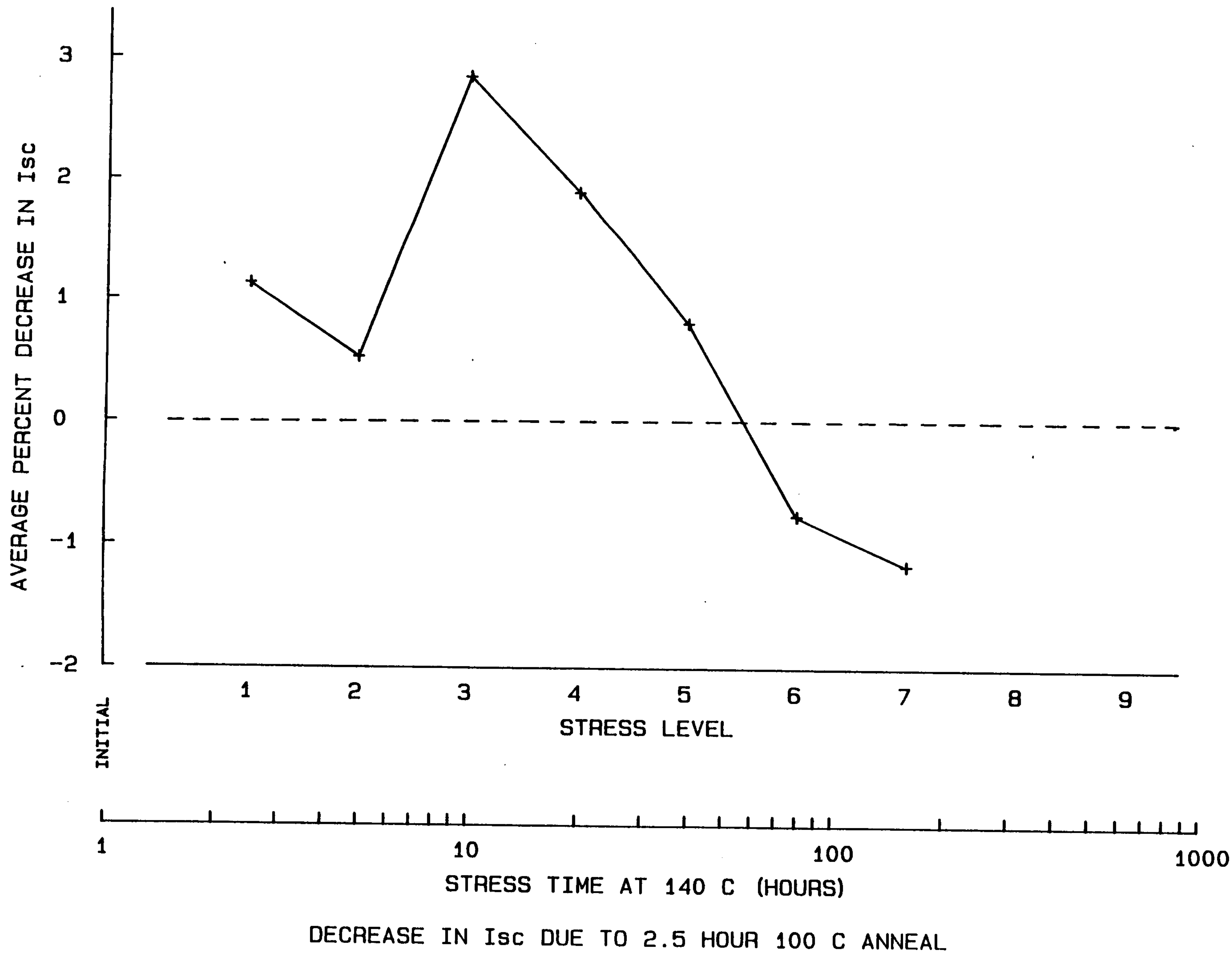


Figure 23. Percent Change in Isc from Annealing Cycle on Type "C" Module

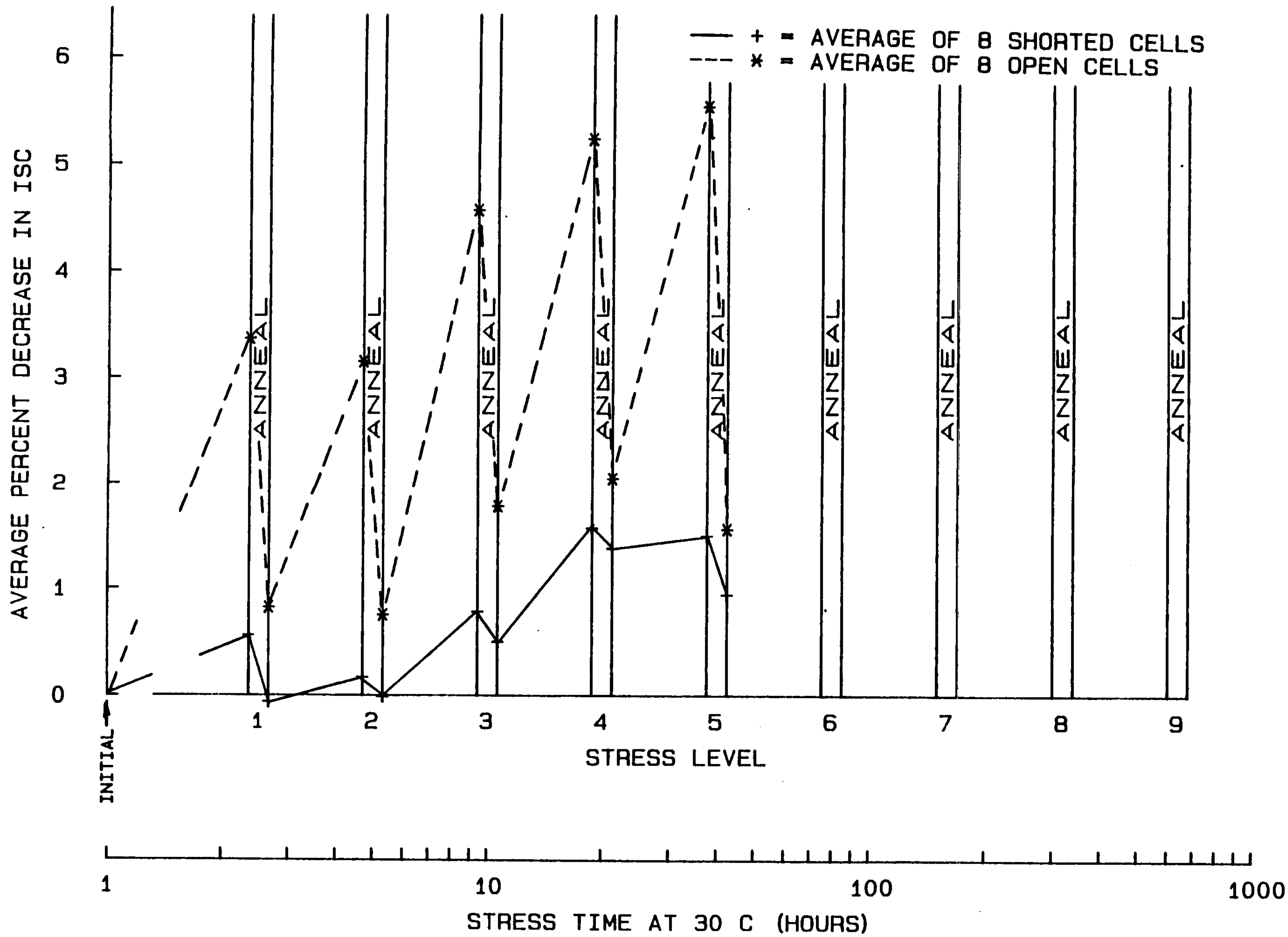


Figure 24. Isc vs Illuminated Time at 30 C for Type "C" Control Module

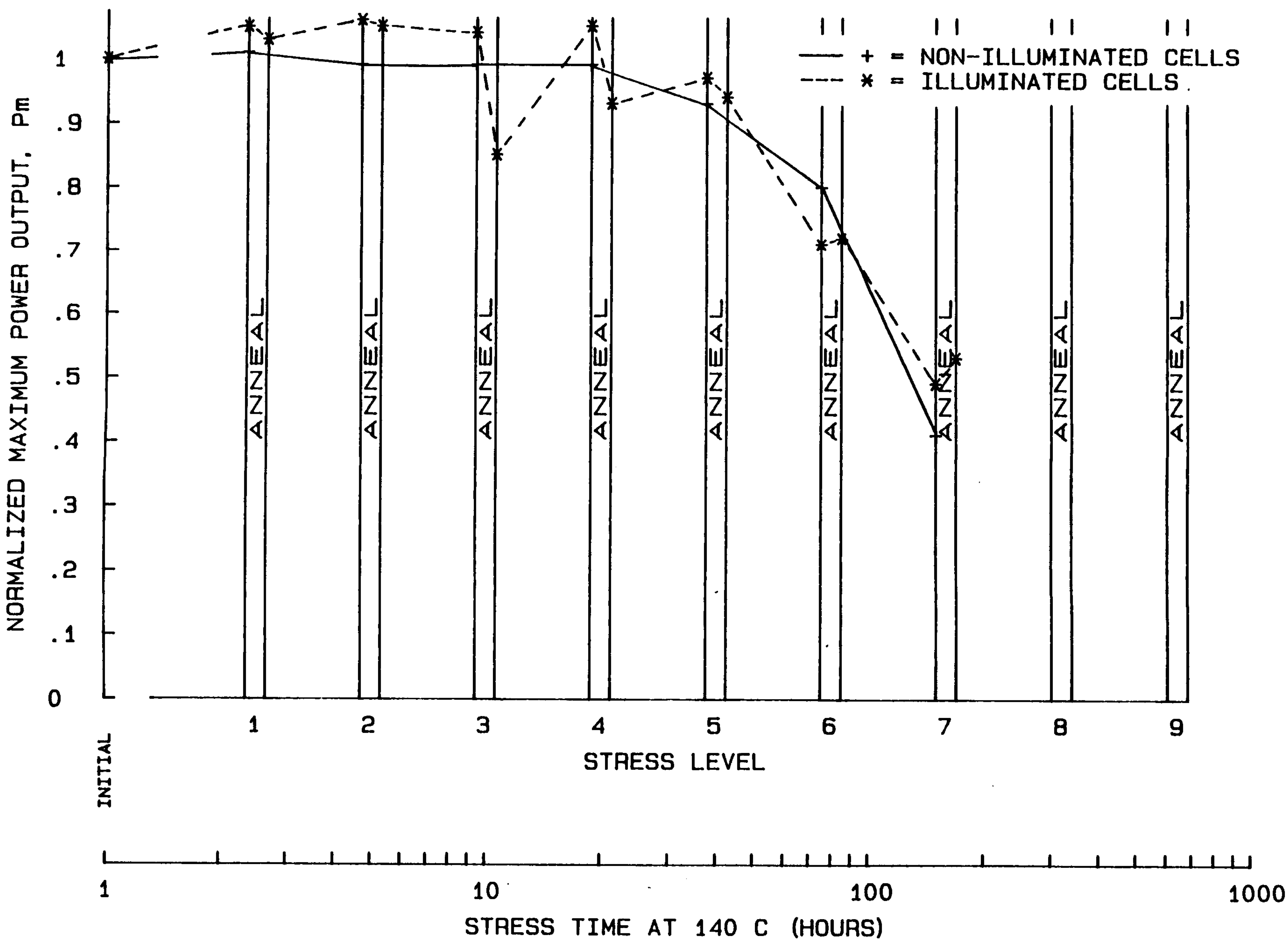


Figure 25. Comparison of Pm vs 140 C Stress Time for Illuminated and Non-illuminated Type "C" Modules

and 20). Both the illuminated cells and the non-illuminated cells show a loss of about 50% of their initial power after 150 hours of stress. Thus long term irreversible degradation appears to be independent of illumination. Some slight improvement in Voc at short stress intervals can also be seen under both conditions.

Finally, illuminated and non-illuminated testing was performed on "E" type cells from the third manufacturer. Figures 26, 27, and 28 summarize the results of stressing at 140 C in the dark on Pm, Voc, and Isc respectively. This module was also quite uniform with all cells having high Voc values and hence little initial improvement was noted. Although no improvement was noted during the first 2.5 hours of stress, improvement was noted at subsequent stress times with a maximum of 3.5% increase in Pm after 20 hours. The maximum power output decreased rapidly after 100 hours of stress and a 50% loss was observed after approximately 300 hours. Eight of the module cells were shorted during stress while 7 were left open and separate avaerages are plotted for Pm and Voc. Because the average values of Isc were nearly identical for shorted and open cells all 11 cells were used for a single Isc plot. Open and shorted cells behaved in a functionally similar manner, with the open cells degrading at a slightly more rapid rate than shorted cells -- the opposite of what was observed on the "A" cells. (Compare Figures 16 and 26.) This supports the earlier conclusion that any difference in degradation between open and shorted cells is probably only due to a statistical fluctuation in test populations.

Figures 29, 30, and 31 summarize the results of subjecting a type "E" module to 140 C illuminated stress on Pm, Voc, and Isc respectively. This module consisted of only high Voc cells.(13 cells). It is interesting to note

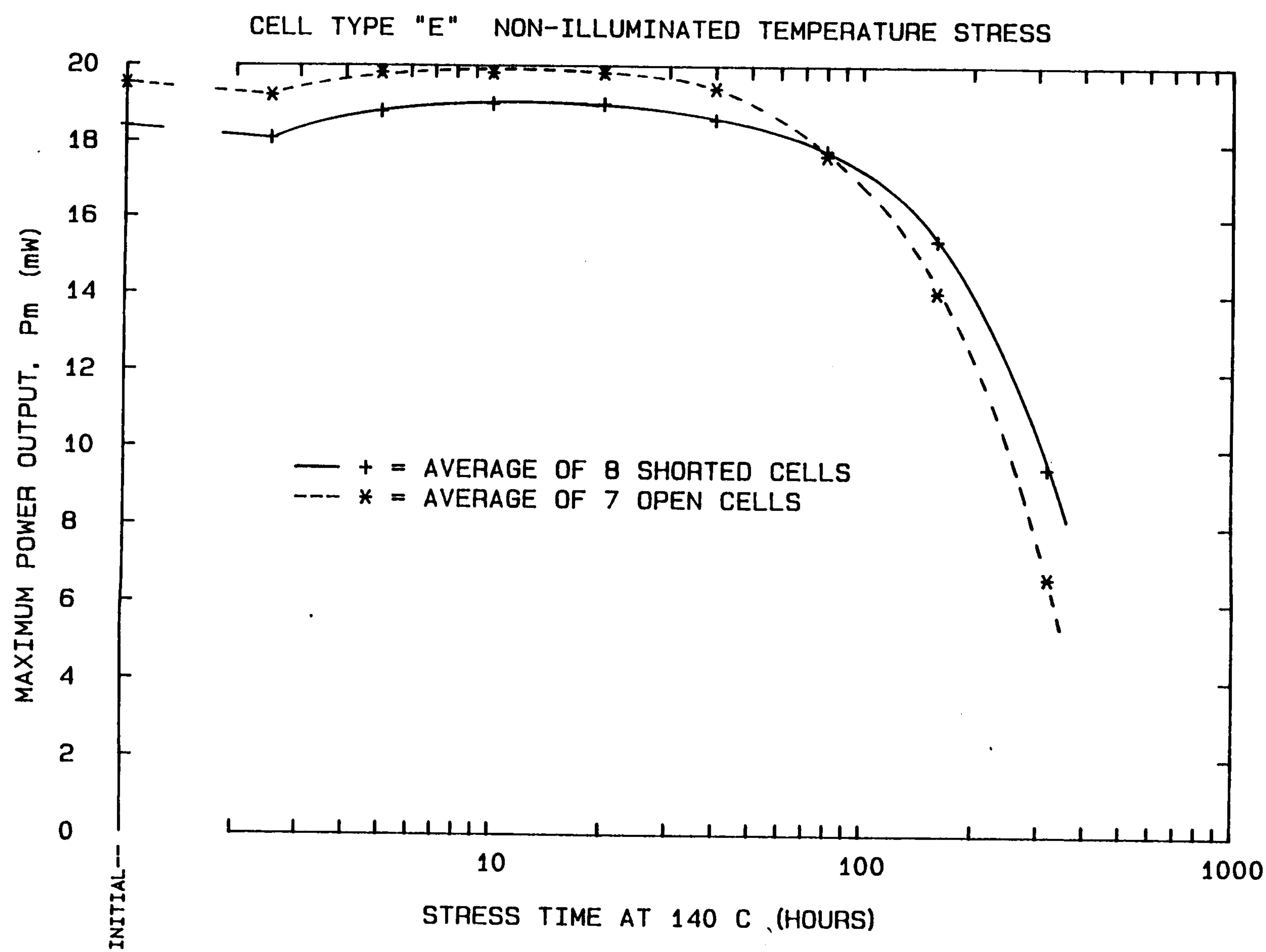


Figure 26. Pm vs Non-illuminated 140 C Stress Time for Type "E" Module

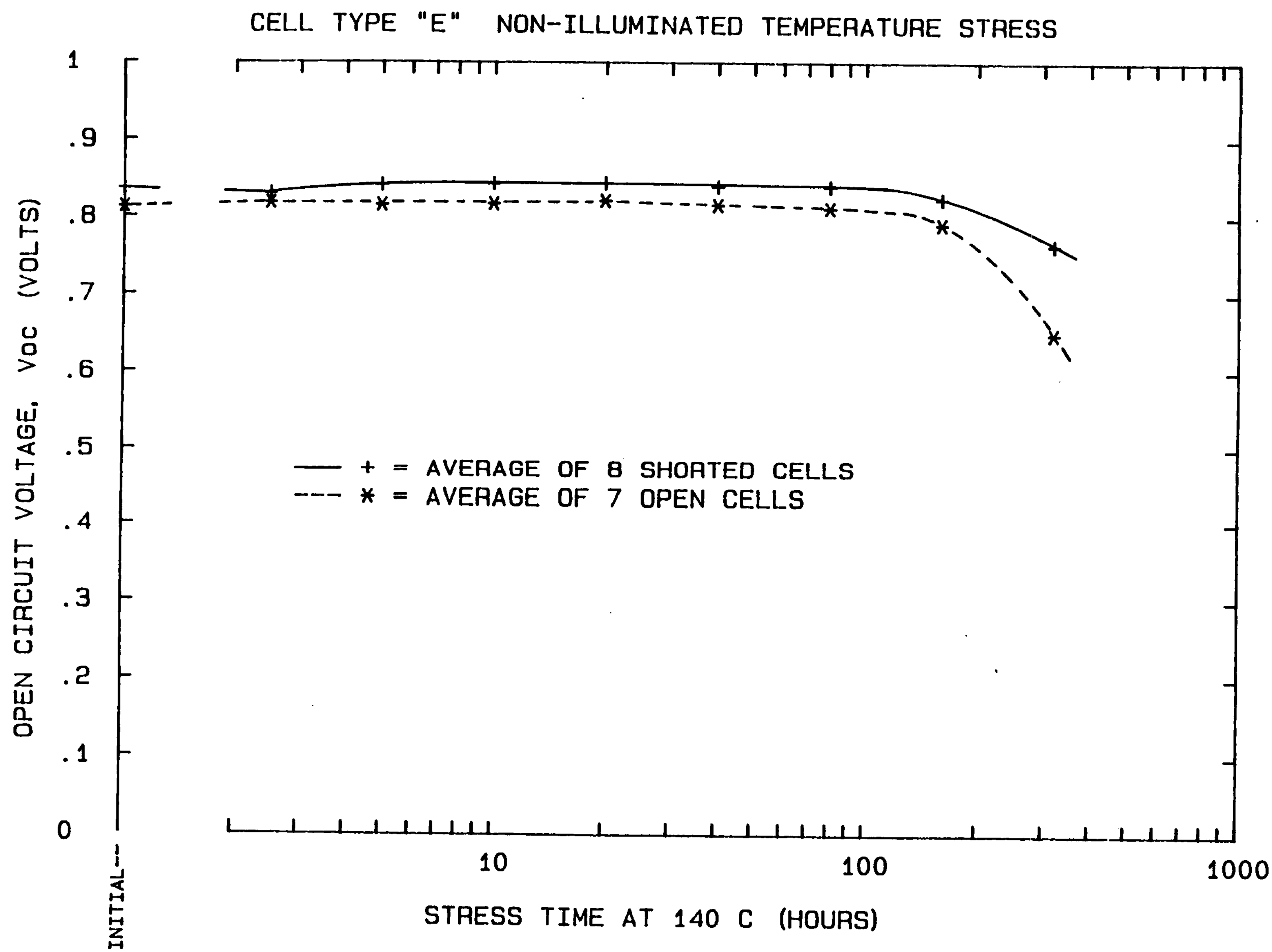


Figure 27. Voc vs Non-illuminated 140 C Stress Time for Type "E" Module

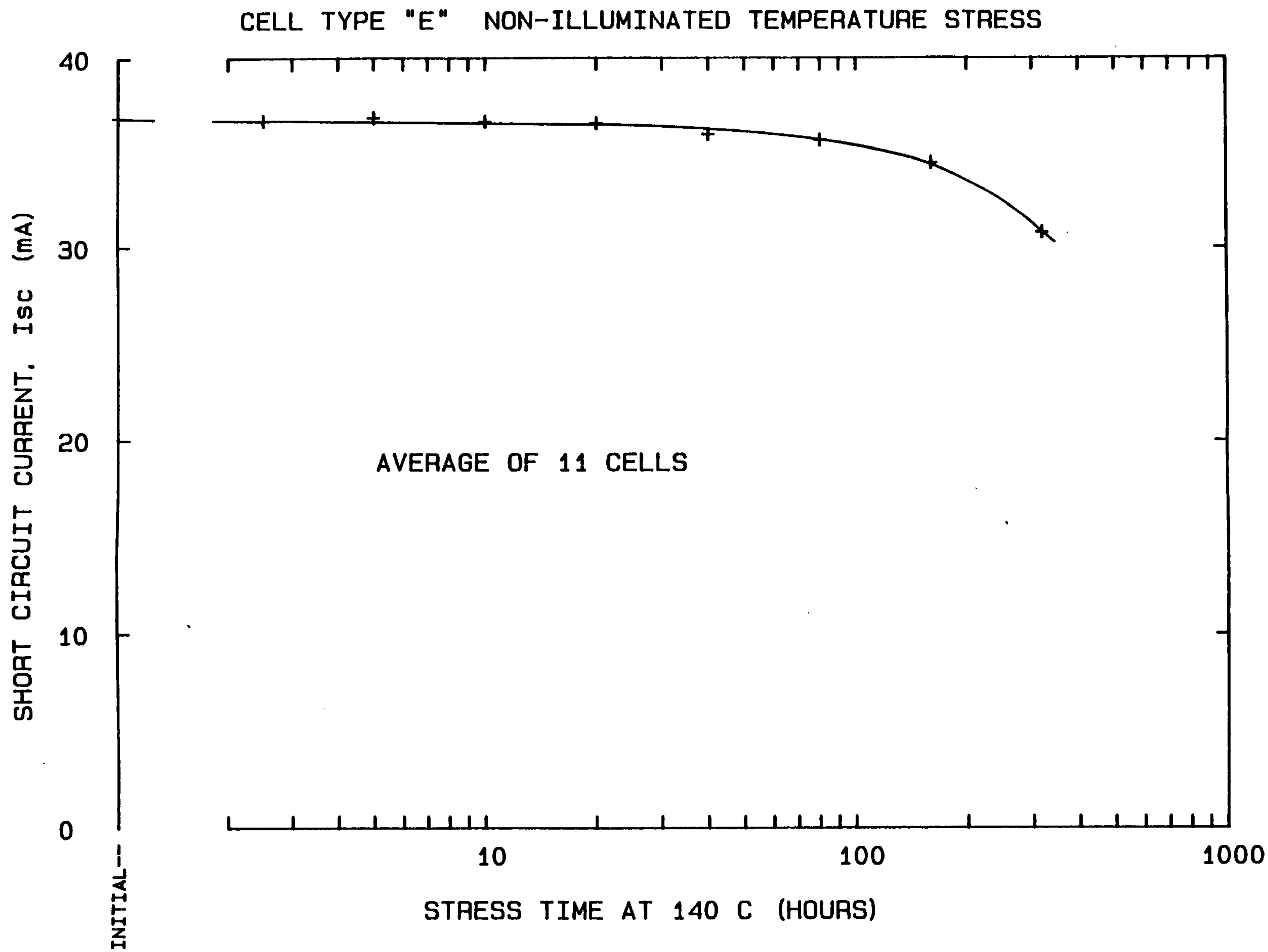


Figure 28. Isc vs Non-illuminated 140 C Stress Time for Type "E" Module

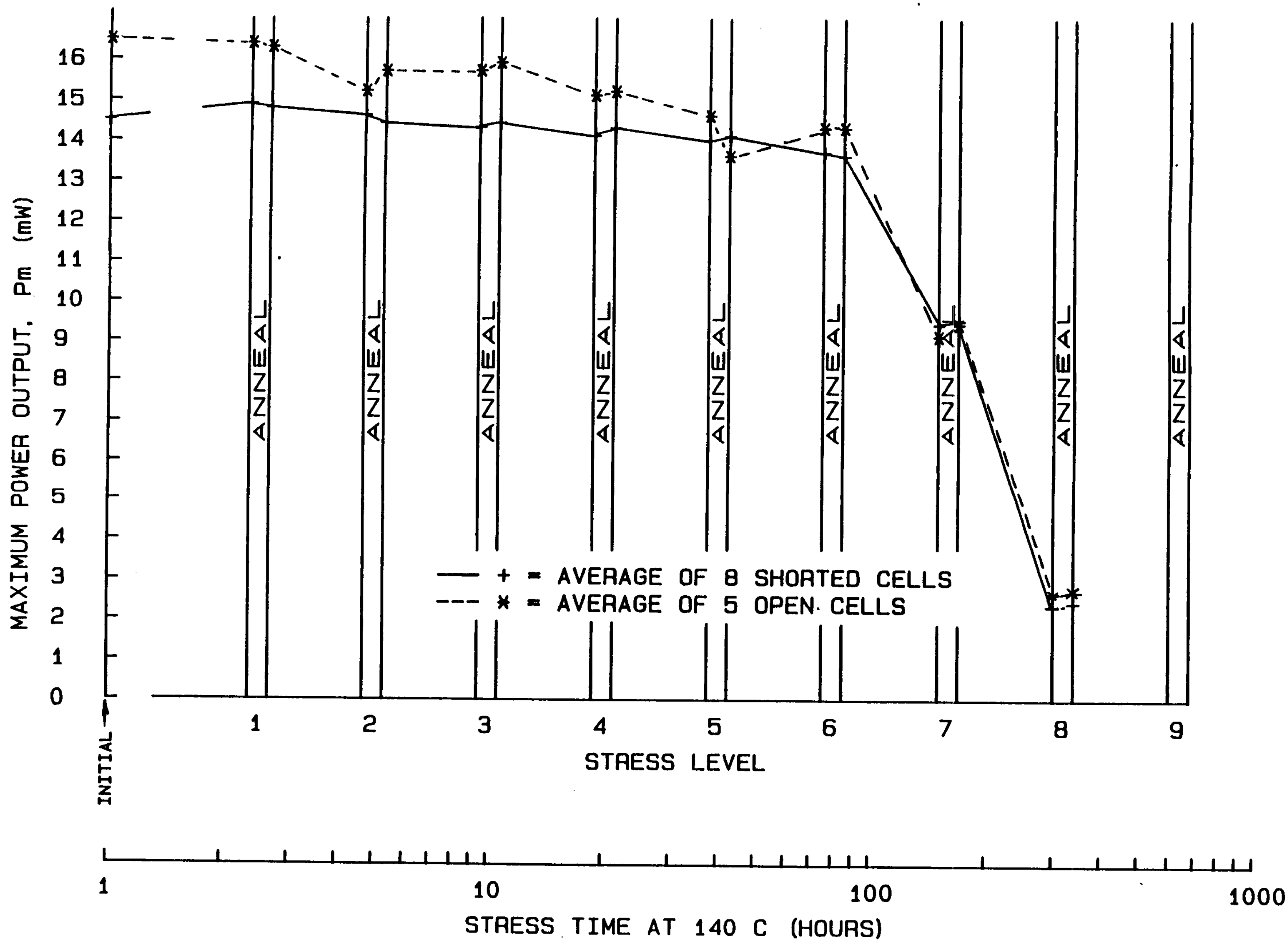


Figure 29. Pm vs Illuminated 140 C Stress Time for Type "E" Module

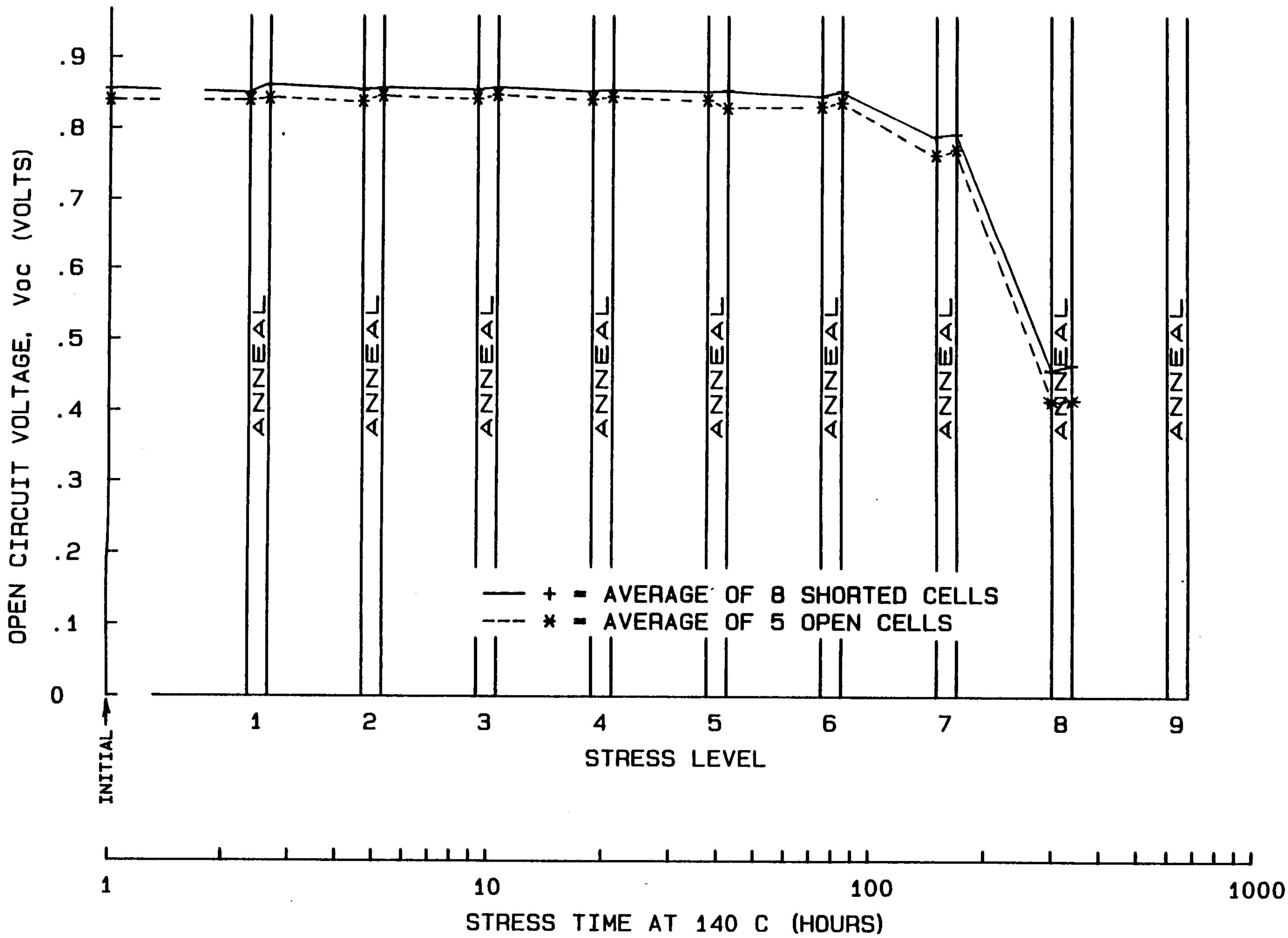


Figure 30. Voc vs Illuminated 140 C Stress Time for Type "E" Module

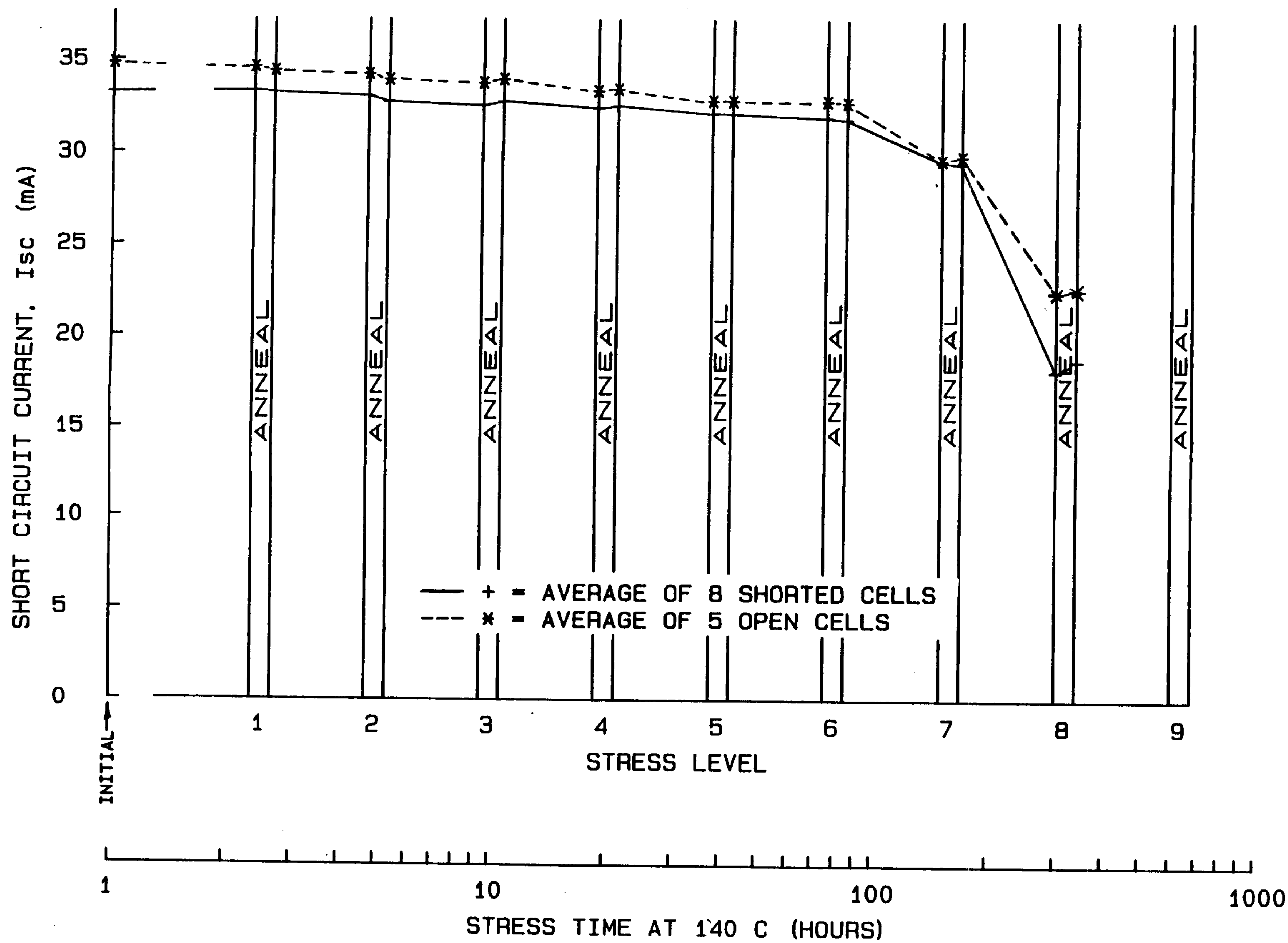


Figure 31. Isc vs Illuminated 140 C Stress Time for Type "E" Module

that the anneal cycle has almost no affect for this type module. A control module "stressed" at 30 C was measured and annealed at the same times as the 140 C stressed module with the result shown in Figure 32. Although a Staebler-Wronski type effect is evident, it is not nearly as clearly defined as in the case of the Type "C" module (Figure 24). It thus appears that "E" module processing has been able to surpress light induced degradation. Figure 33 compares illuminated and non-illuminated testing. It appears that the illuminated cells fall off somewhat more rapidly than the non illuminated cells, but the difference in not felt to be significant.

Figures 34 and 35 are examples of before and after stress VI characteristics for illuminated 140 C stress respectively. Cell #6 was shorted while stressed and cell #10 was open. Both cells show the effects of rectifying contact formation after 320 hours. This effect had been noted on certain types of crystalline cells, but this is the first evidence of occurrence in amorphous cells. There was insufficient time to investigate this behavior further, but it is felt to indicate a different type of degradation for the "E" cells.

In addition to subjecting single junction amorphous cells to accelerated stress testing, preliminary tests were made on one type of commercial tandem junction amorphous cell. As shown in Figure 36 for a typical module, these cells, which all had uniformly high Voc values, also showed an initial increase in Voc followed by long term degradation when stressed in the dark under open circuit conditions. However the Voc changes (and associated Pm changes) were very small, less than 5%, even when stressed at temperatures as high as 180 C for 1000 hours (Contrast Figure 36 with Figures 6, 14, 17, etc.)

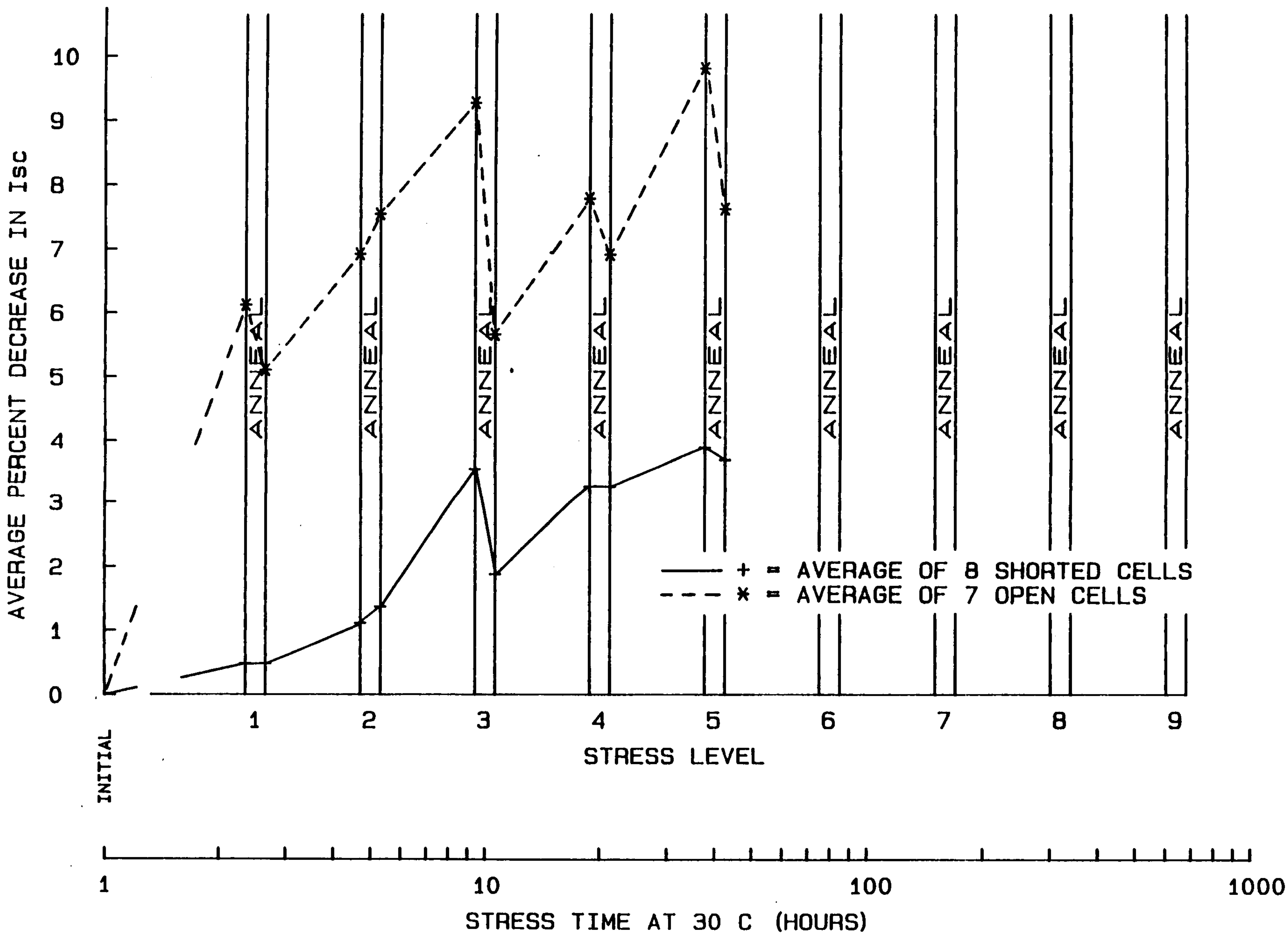


Figure 32. Isc vs Illuminated Time at 30 C for Type "E" Control Module

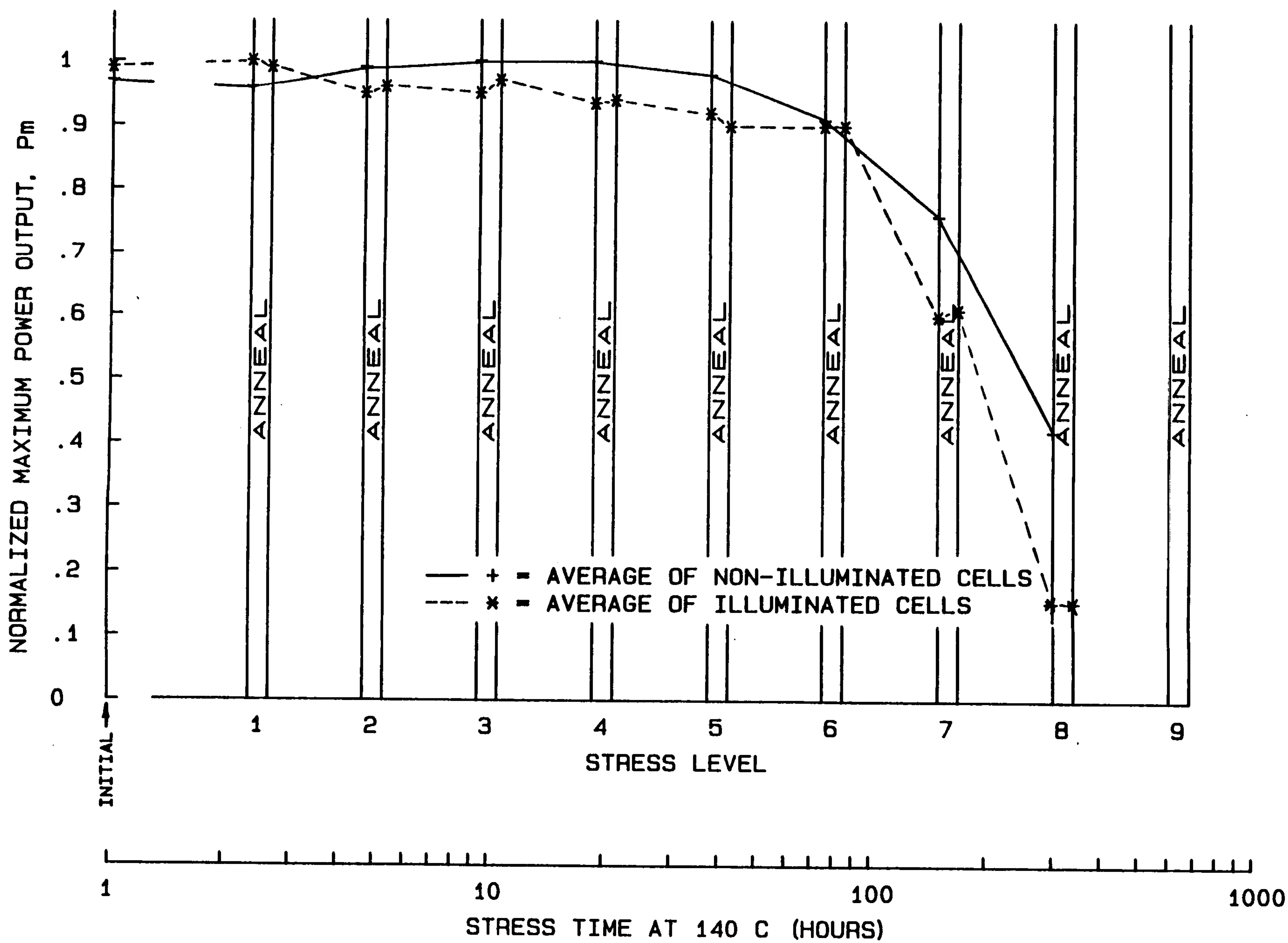


Figure 33. Comparison of Pm vs 140 C Stress Time for Illuminated and Non-illuminated Type "E" Modules

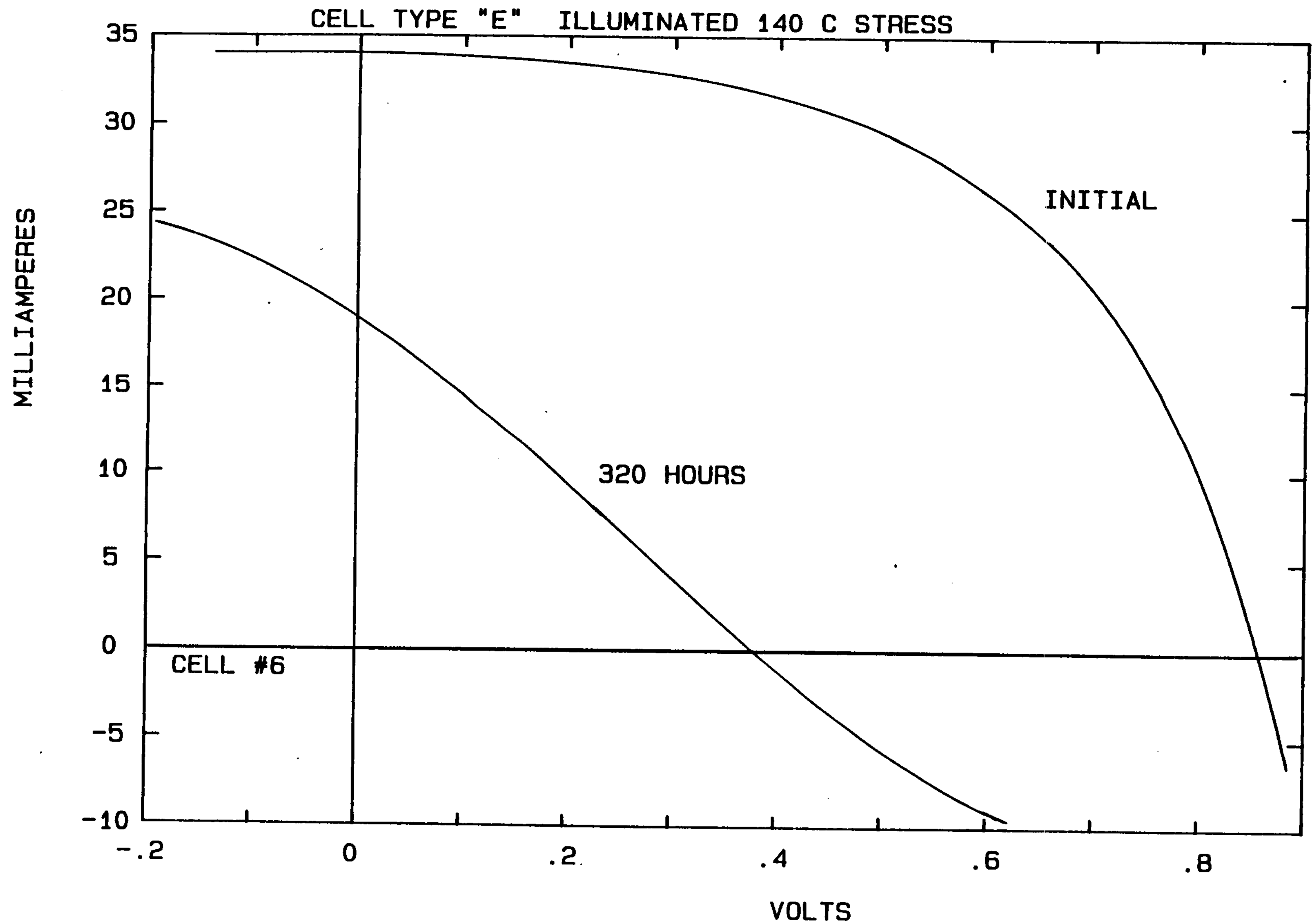


Figure 34. VI Characteristics for Cell #6 from Type "E" Module

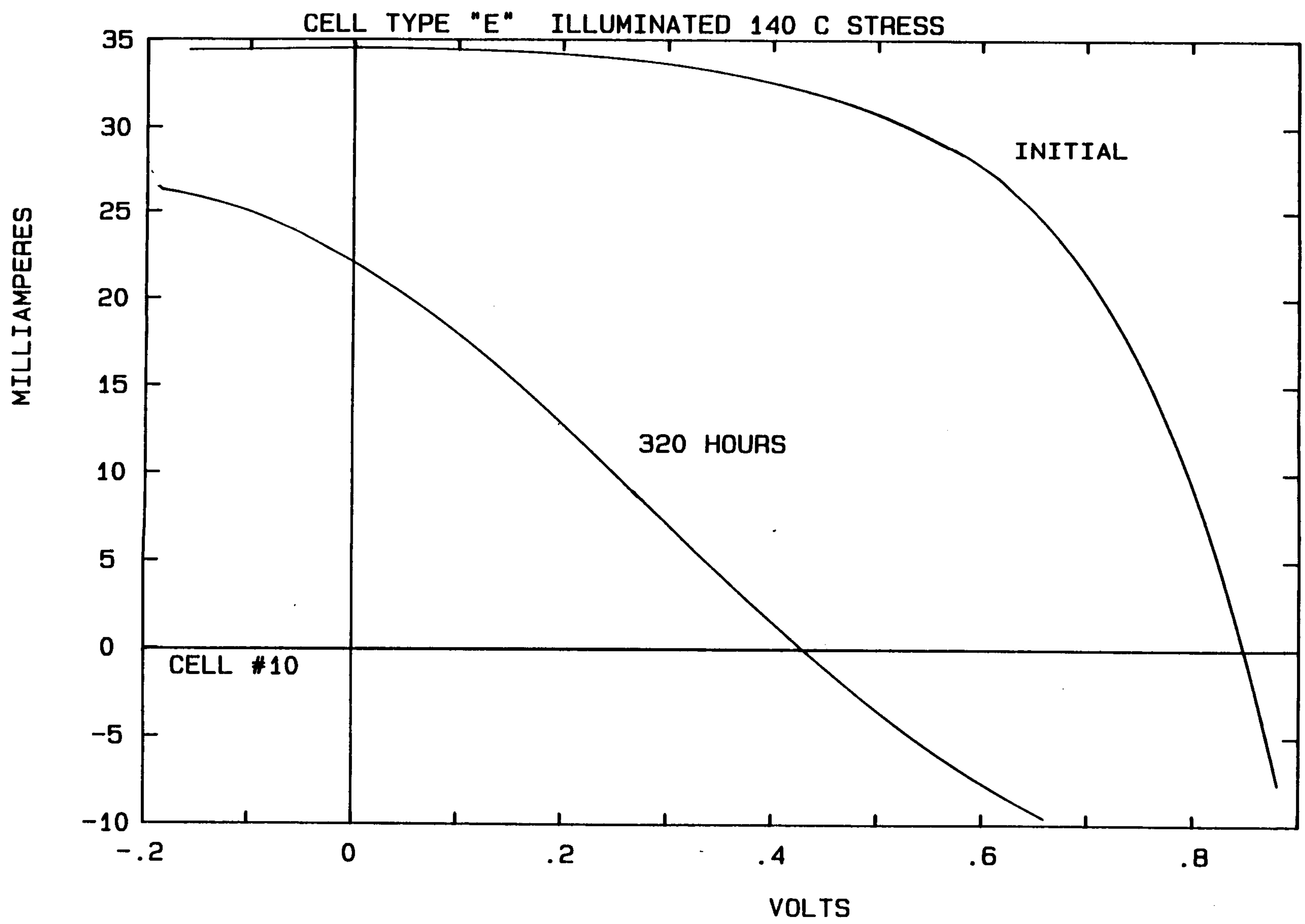


Figure 35. VI Characteristics for Cell #10 from Type "E" Module

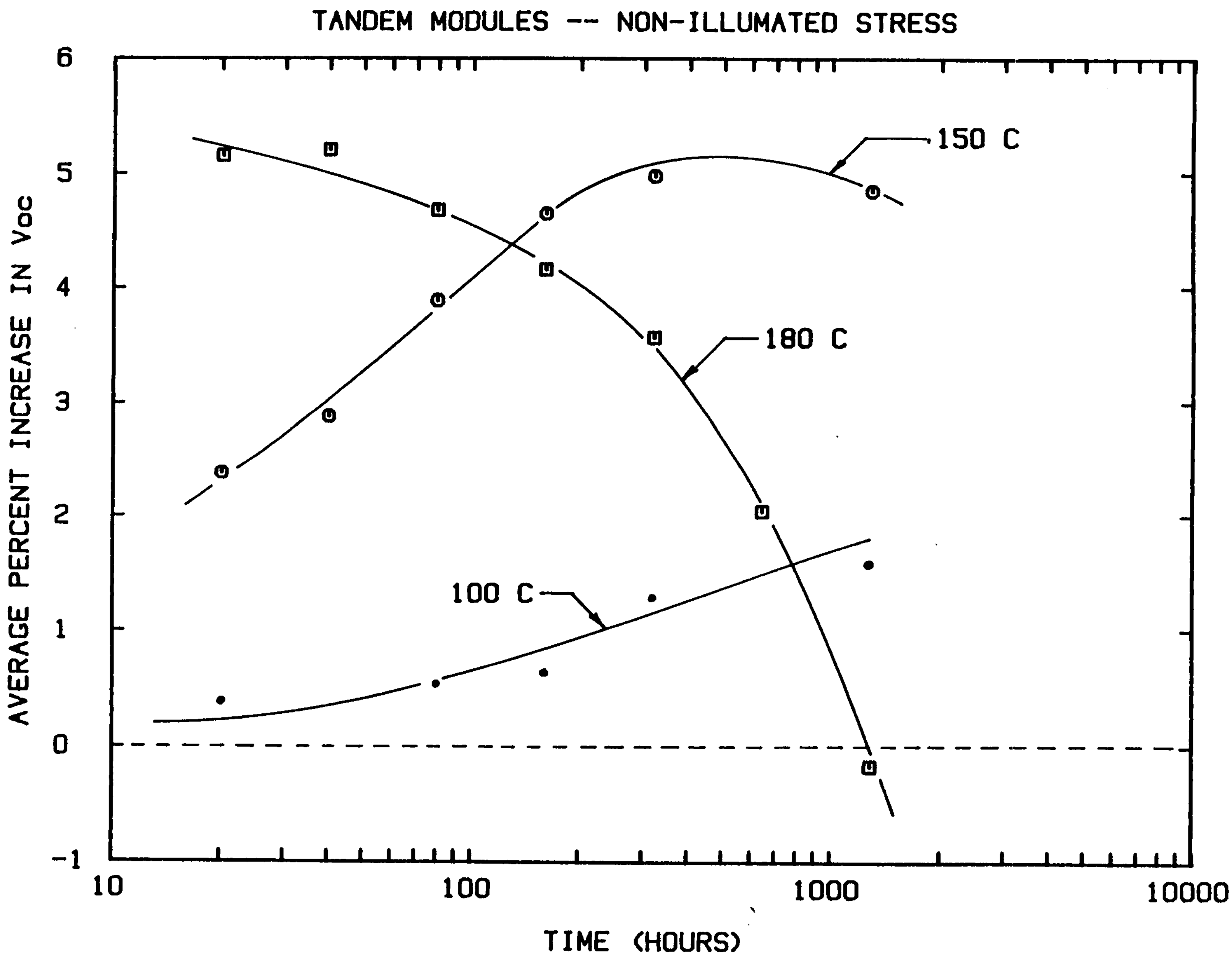


Figure 36. Voc vs Stress Time for an Amorphous Silicon Tandem Cell Module

An Arrhenius type behavior is noted in Figure 36 with Voc increasing more quickly and degrading more rapidly as the tempreature is increased. The relatively small long term Voc decrease was partially offset by a corresponding increase in Isc, as a result of the cell's tandem construction, so that the maximum output power decrease that was observed under the particular ELH spectral conditions used was minimal.

4.0 CONCLUSIONS

4.1 Electrical Behavior of Stressed Amorphous Cells

The three types of single junction amorphous cells tested thus far responded quite differently from crystalline cells to accelerated stress. Testing indicated the presence of a mechanism which tends to improve the characteristics of low Voc cells. One module type, Type "A", which had a 50-50 mixture of high and low Voc cells, showed dramatic improvement in the low Voc cells after less than 20 hours of stress at 140 C. Another module. Type "B", which a higher percentage of low Voc cells showed no improvement, while module types "C" and "E", which consisted only of high Voc cells, showed only small amounts of improvement. Cells in tandem module type "F" also showed a tendency towards improvement at low stress levels. Data on stressed amorphous cells presented by Fukada, et al (18) showed similar initial improvement, although the improvement which they observed was much less than that measured on cell Type "A". These results lead to the first conclusion:

Small amounts of thermal stress can correct some cell defects introduced during manufacture.

The physical nature of these process induced defects is not known, but the result is increased cell leakage (decreased shunt resistance) and low Voc.

When stressed at elevated temperatures in the dark all cell types eventually showed ireversible degradation. This also had been observed by

Fukada. Figure 37 is a comparison of maximum power output, normalized to its highest value, vs stress for the 5 cell types tested at Clemson with Fukada's results for comparison. Single junction modules A, B, C, and E were all stressed at 140 C, while the tandem module and Fukada's cells were stressed at 150 C. Consequently the curves for these latter two cell types appear somewhat worse relatively than they should. To avoid confusion individual data points are not indicated in this plot and low stress portions of the curves are shown only for cell types A, B, and Fukada. One type of single junction module, Type "A", degraded to 50% after 2000 hours at 140 C, while the other Clemson single junction modules degraded to 50% between 30 and 300 hours. Fukada's cell degraded to 50% after 50 hours at 150 C and the tandem cell extrapolated to 50% degradation at approximately 10,000 hours at 150 C. Based on these results two additional conclusions can be stated:

All amorphous cell types irreversibly degrade as a result of elevated temperatures and the time to reach 50% degradation can vary by orders of magnitude depending on cell construction.

Tandem cells appear to degrade appreciably slower than single junction cells.

It should be noted that only tandem cells had degradation rates as low as those of crystalline cells. Whereas classical Staebler-Wronski light induced degradation was clearly evident in control modules at room temperature, modules stressed in light at elevated temperature did not show such an effect. When single junction cells were stressed at elevated temperatures in the light

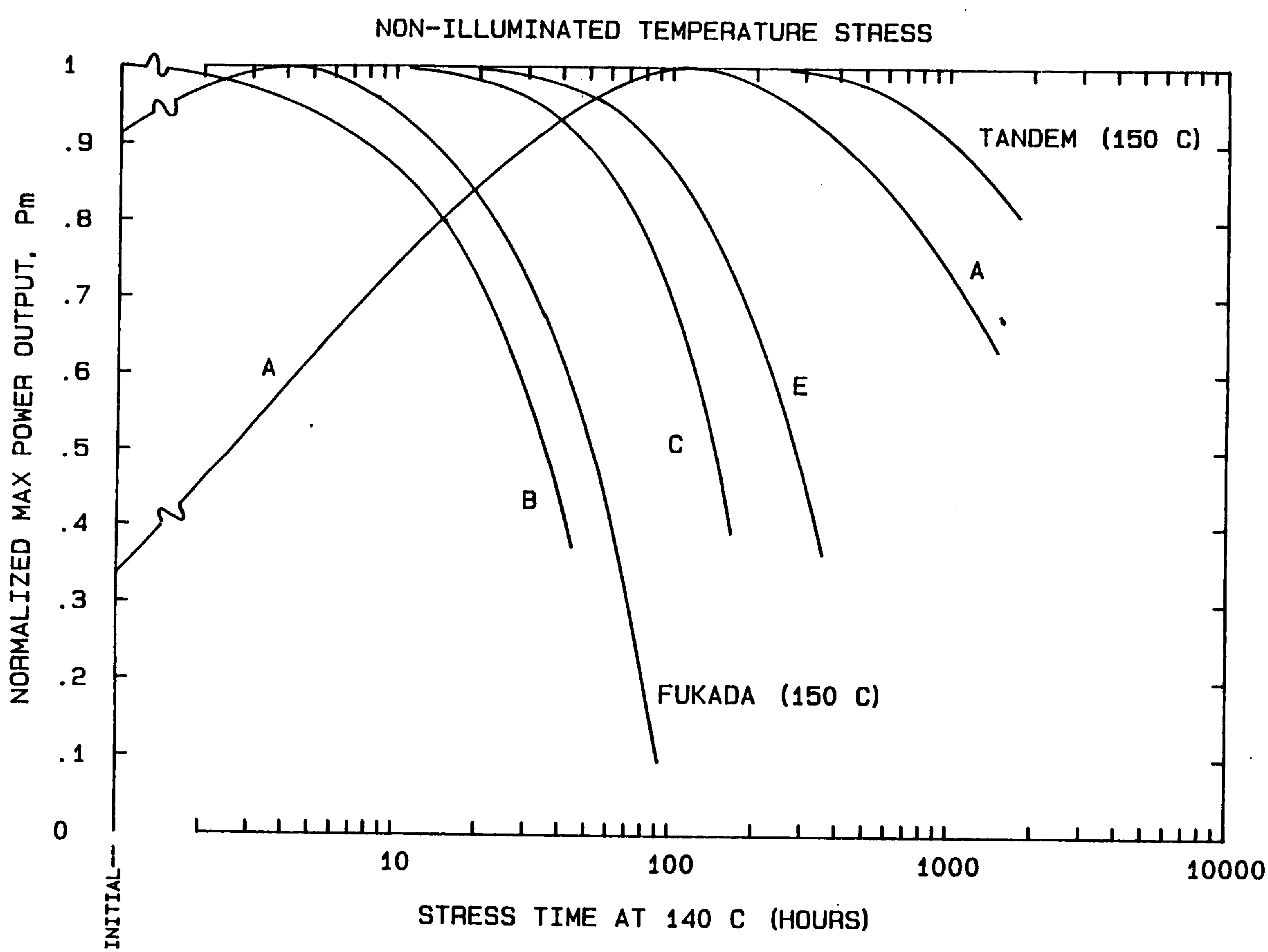


Figure 37. Normalized Pm vs Non-illuminated Stress Time for Various Type Modules

the long term degradation was essentially the same as in the dark, but the effect of a low temperature anneal was to reduce rather than improve cell parameters. Little discernable difference could be seen between cells which were open circuited and short dircuited during either light or dark elevated temperature stressing. This leads to the conclusion that:

> The long term degradation characteristics of amorphous cells can be obtained by elevated temperature stressing in the dark without the need for illumination or electrical connections to the cells.

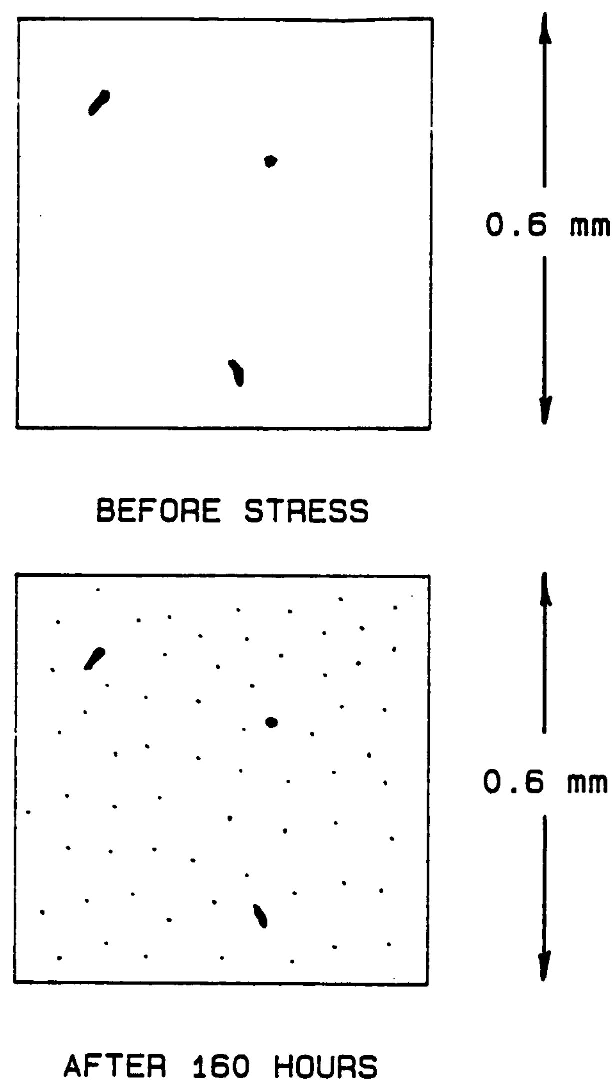
This greatly simplifies accelerated stress testing procedures and makes possible rapid, large scale testing.

4.2 Physical Basis of the Observed Degradation

Fukada, et al attributed the degradation of their cells to aluminum diffusing from the back contact into the active amorphous film and presented SIMS data as substantiating this. Tawada, et al (19) reported on the use of barrier layers to prevent the diffusion of aluminum. As a result of these papers and the similarity of observed effects, aluminum diffusion was considered a prime suspect. The diffusion coefficient of aluminum at 140 C, however, could be shown to be insufficient to account for the observations, even allowing for modifications due to the use of amorphous rather than single crystal material. Another possibility was silicon dissolving in the aluminum to the limit of its solid solubility. However, an Auger analysis indicated that approximately 1 to 1.5% silicon had been added to the aluminum, i.e. the aluminum had been purposely saturated to prevent this.

It is more likely that a phase transformation is occurring at the contact interface resulting in the formation of an aluminum silicon compound. Examination of the aluminum coated back of cells by means of infra-red illumination transmitted from the front using a Research Devices IR microscope, Model F, revealed voids on Type "C" cells after stress not visible with an optical microscope. A diagram showing typical before and after stress patterns is shown in Figure 38. (Because the microscope camera had not yet been received it was not possible to photograph the patterns.) The diagram is drawn for simplicity as a negative of the observation, i.e. a bright "star" pattern was observed on a dark background. Since silicon is transparent to IR while aluminum is opaque, this was evidence that aluminum next to the silicon at these points must be "spiking", i.e. rapidly disappearing, into the silicon even though the stress temperature is well below the silicon-aluminum eutectic temperature.. The intensity of the rather uniformly distributed "stars" was less than that from adjacent pinholes and flaws initially present in the aluminum film, some of which are shown in Figure 38. This indicates that a thin undisturbed layer of aluminum was still in place at the surface, which is why the "stars" could not be detected optically.

After IR examination at 160 hours the "C" cell sample was placed back in the 140 C oven for additional stressing. The stars gradually increased in size and at 700 hours had become barely visible with an optical microscope. At this point the sample was examined by energy dispersive x-ray (EDX) spectroscopy using a JOEL 848 electronmicroscope. An EDX map of the aluminum surface clearly showed the presence of localized silicon. Diagrams of the aluminum and



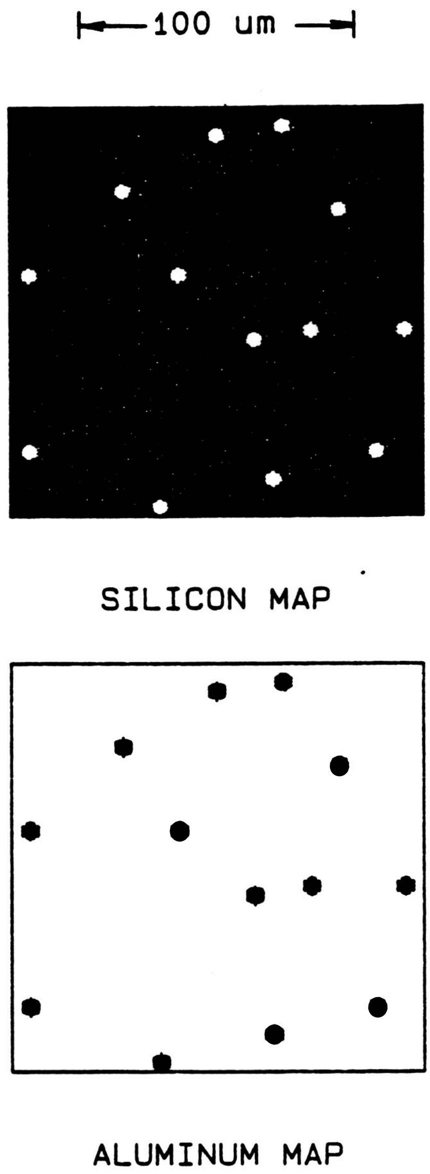
SIMULATED (NEGATIVE) IR MICROSCOPE PATTERNS
CELL TYPE "C", 140 C NON-ILLUMINATED STRESS

Figure 38. IR Microscope Patterns for Stressed and Unstressed Type "C" Cells

silicon map patterns are shown in Figure 39. (It was necessary to generate the diagrams graphically because there was insufficient contrast in the photographs for good reproduction.)

Ion etching techniques were used to obtain Auger and SIMS profiles of the cells. Little additional information concerning aluminum "spiking" was obtained, however, because of the difficulty of locating regions of penetration and termination of the contract. Fukada's SIMS data was obtained using a very large (3 mm) beam diameter so that his data could represent the average of a number of localized points. In the process of examining stressed samples for localized concentrations, one unusual profile, shown in Figure 40, was obtained which indicated the presence of a large accumulation of indium within the amorphous layer. The significance of this accumulation is not known, but it is possible that indium as well as aluminum "spiking" may occur. A comparison of profiles from Type "A" and Type "C" samples (both made by the same manufacturer) indicated that the Type "A" amorphous films were twice the thickness of the Type "C" films. This is significant since the 50 % degradation time for "A" cells was roughly 2000 hours vs 200 hours for "C" cells. This would seem to imply that it is necessary for the aluminum to traverse the complete film thickness before serious degradation occurs.

An examination of other stressed cell types revealed the presence of IR "stars" on all cell types except "E". It is not known if this represents a fundamentally different type of degradation mechanism for Type "E" cells or if the difference is due merely to a greater aluminum thickness effectively blocking IR transmission. However, as was pointed out in Section 3, the "E" cell was the only type whose stressed VI characteristics exhibiting rectifying



COMPUTER GENERATED EDX MAPS OF TYPE "C" CELL

BACK CONTACT AFTER 700 HOURS AT 140 C

Figure 39. EDX Maps of Stressed "C" Cell Aluminum Back Contact

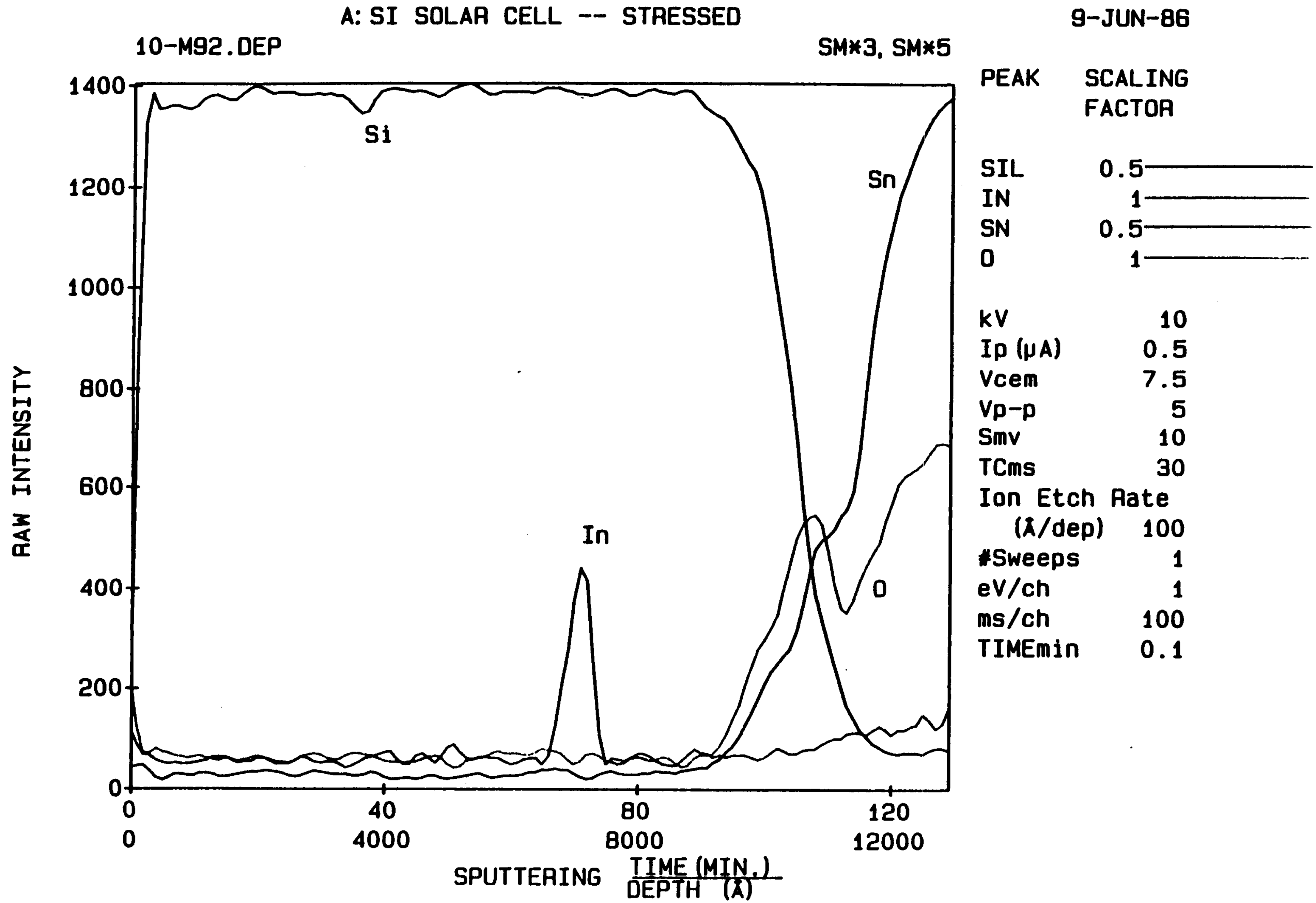


Figure 40. Auger Profile Example Showing Indium Concentration

contact behavior. This would seem to confirm that the aluminum contact - silicon interface was being affected in a uniform manner rather than by localized spiking.

The investigations described above, although incomplete, lead to the following conclusion:

The most likely cause of irreversible cell degradation appears to be aluminum penetration of the amorphous cell at localized sites.

The reason for this penetration remains unknown. The best guess is that it is due to inhomogeneities in composition of the layers involved rather than the presence of an interface layer. If the initial distribution of silicon in the aluminum contact varied spatially, compound formation might be initiated at points of low silicon concentration. The use of barrier layers, as described by Bower (20), could be used to delay the onset of compound formation. Obviously more work is needed in this area.

4.3 Further Work

For all of the modules discussed in this report, accelerated stress data was taken at only a single temperature, usually 140 C. As a result of step stress testing performed on the modules and reported in the previous annual report no abrupt transitions were noted at temperatures as low as 140 C and it appears reasonable to assume that the degradation mechanisms can be extrapolated to use conditions by means of an Arrhenius relationship and knowledge of the appropriate activation energy. In order to determine an activation energy for the degradation mechanism, however, it is necessary to perform stress testing at at least three different temperatures. If a commonly assumed activation energy of 0.5 eV is used, then stress at 140 C represents an acceleration factor of about 200 over room temperature. Consequently a 50% power reduction after 10,000 hours at 140 C (tandem module) would extrapolate to 200 years at 30 C, while 30 hours (Type "B" Module) would only extrapolate to less than a year! While accelerated testing at a single temperature can indicate the relative reliability attributes of different cells it gives little information on absolute degradation time. Therefore,

IT IS CRUCIAL THAT ACTIVATION ENERGIES BE MEASURED IN ORDER TO DETERMINE IF SERIOUS RELIABILITY PROBLEMS EXIST.

The failure analysis described in this report represents only a beginning. It has pointed to localized penetration of the aluminum through the active amorphous film as the cause of long term degradation. Much more extensive analysis will need to be conducted in conjunction with corrective process and material modifications. Solution of the problem will be an iterative process over a period of time.

Essentially nothing is known concerning the origin of the initial improvement noted on low Voc cells made on thick films. Investigative work should be performed to understand this effect as there is the potential of using it to make high quality modules with superior reliability characteristics.

5.0 NEW TECHNOLOGY

Descriptive Title: Improved Performance of a-Si:H Solar Cells Through Burn-in.

Name of Innovator: Jay W. Lathrop

References: DOE/JPL-954929-85/12, pp.37-38, November 1985
DOE/JPL-954929-86/13, pp.15-24, September 1986

Discussion: The large initial improvement observed when cells with low Voc are subjected to temperature stress testing should be considered an item of new technology. When the effect is understood better it may be possible to incorporate some form of module burn-in during processing which would improve the performance of poor cells while not appreciably degrading the good cells.

6.0 PROGRAM RESEARCH CONTRIBUTIONS

Since the previous annual report was issued, the project has made a number of documented contribution to the photovoltaic community. These are summarized in this section.

Publications and Presentations:

Lathrop, J.W. and Royal, E., "Observed Changes in a-Si:H Cell Characteristics Due to Long-Term Temperature Stress," Proceedings of 18th IEEE Photovoltaic Specialists Conference, Las Vegas, NV, October 1985, pp. 481-486.

Davis, C.W. and Lathrop, J.W., "Repeatable Measurement Methods for use in Accelerated Stress Testing Thin Film Solar Cells," Proceedings of 18th IEEE Photovoltaic Specialists Conference, Las Vegas, NV, October 1985, pp. 1693-1697.

Lathrop, J.W. and Royal, E.L., "Accelerated Stress Testing of a-Si:H Solar Cells," 2nd International Photovoltaic Science and Engineering Conference, Beijing, China, August 1986, pp. 386-389.

Lathrop, J.W., Davis, C.W. and Royal, E.L., "Accelerated Stress Testing of Commercial a-Si:H Solar Cells," 7th European Photovoltaic Solar Energy Conference, Sevilla, Spain, October 1986 (accepted for publication)

Thesis:

Hefley, P.L., "Accelerated Stress Testing of Tandem Amorphous Solar Cells," MS Electrical Engineering Thesis, Clemson University, August 1985.

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APPENDIX A

Accelerated Stress Testing of a-Si:H Cells
J.W. Lathrop and Edward L. Royal

Presented at

2nd International Photovoltaic Science and Engineering Conference

Beijing, China (August 19-22, 1986)

Preprint: 2nd International Photovoltaic Science and Engineering Conference
Beijing, China (August 19-22, 1986)

Accelerated Stress Testing of a-Si:H Cells (*)

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ABSTRACT

Determination of thermally induced degradation mechanisms affecting thin film amorphous silicon solar cells through the use of laboratory accelerated stress testing requires stressing cells at elevated temperatures under both light and dark conditions in order to separate short-term optically induced defects from long-term irreversible effects. This paper describes accelerated temperature stress procedures and test results for several types of single junction and one type of tandem junction a-Si:H cells. Two degradation mechanisms appear present -- one leading to short term improvement and one leading to long term irreversible degradation. Light does not appear to appreciably affect either mechanism, but annealing in the dark causes cells improved by short term light/temperature stress to degrade, which is opposite to the conventional Staebler-Wronski effect. The tandem cell appeared much less susceptible to long term degradation than the single junction cells.

INTRODUCTION

Accelerated test methodology involves subjecting cells to stresses higher than normally encountered during use in hopes that naturally occurring degradation mechanisms, which might take years to detect in the field, can be detected in the laboratory within days or weeks. Cells which have been visually inspected and electrically measured are subjected to the desired level of stress and then measured and inspected again. Observed changes are then assumed to be due to the effect of stress and, through analysis of the degradation, related to fundamental physical, chemical, or metallurgical changes. In this way accelerated stress testing can be used to uncover potential failure mechanisms in a relatively short period of time.

Laboratory accelerated testing of individual crystalline solar cells has proven to be a valuable tool for determining the reliability attributes of this technology. However, thin film modules are fabricated monolithically, i.e. a number of interconnected cells are fabricated simultaneously on a single substrate or superstrate eliminating the possibility of physically separate cells. Furthermore, because of the relatively high sheet resistances involved, the physical shape of each individual cell in a series connected module is that of a long thin rectangle. In order to individually measure a-Si:H cells in monolithic structures taken directly from a manufacturer's current production prior to encapsulation and avoid the averaging and mismatch effects inherent in module testing, special contacting techniques had to be developed.

(*) Work supported in part by JPL under Contract DOE/JPL - 954929

EXPERIMENTAL PROCEDURE

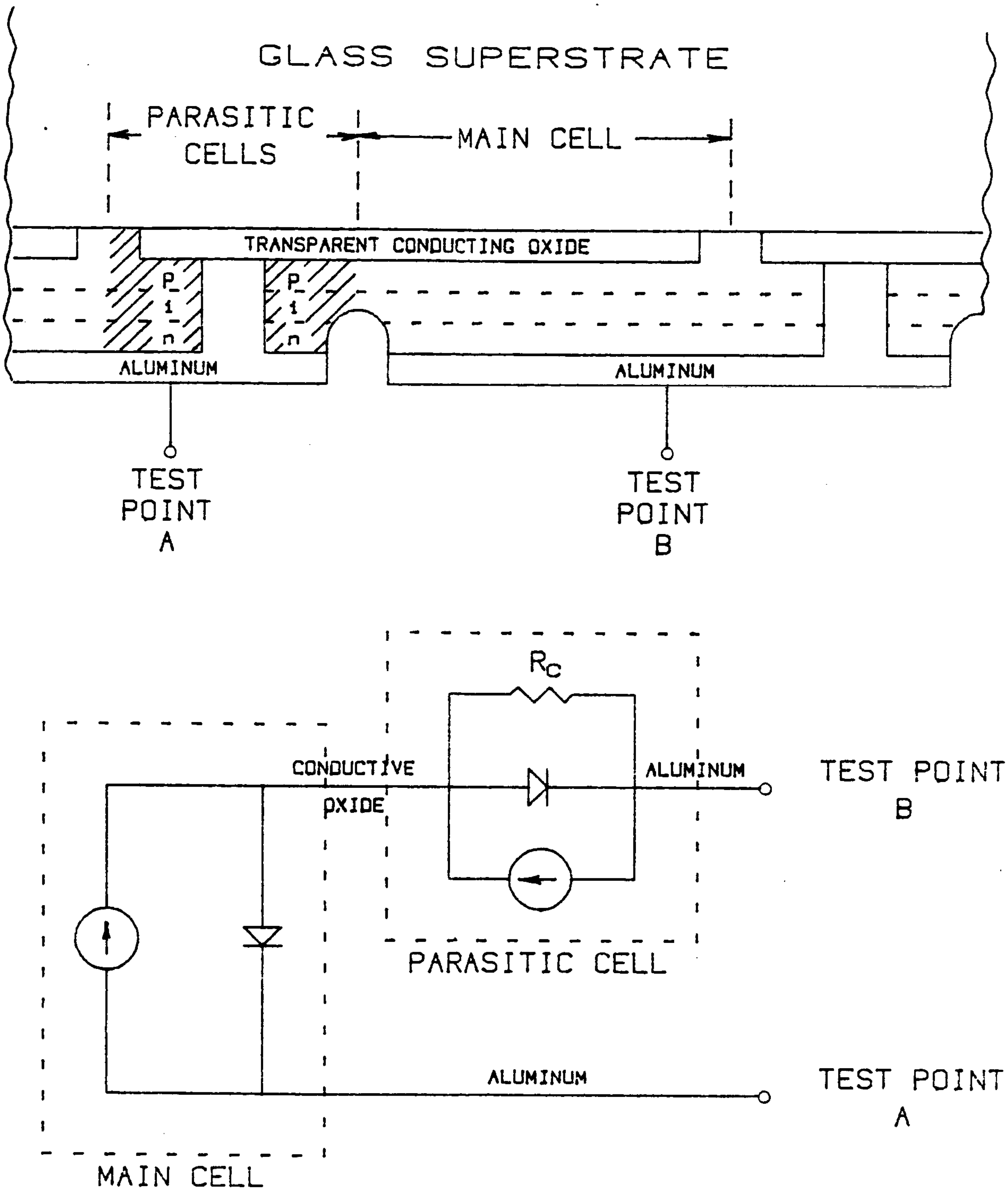
In the series connected type of construction, connection to the front of the cell under test is made from the back of an adjacent cell as shown in Figure 1(a). Test point A connects to the transparent conducting oxide of the main cell while test point B contacts the back of the main cell. The lumped constant equivalent circuit including the presence of the parasitic cell is shown in Figure 1(b).

To avoid contact series resistance effects, separate voltage and current probes need to be used at both test point A and test point B. After extensive investigation the only technique found to be completely repeatable was to permanently attach parallel wires the length of each contact using conductive epoxy. The conductive epoxy used was Type K Microcircuit Silver made by Transene Co. Inc. Rowley, MA, USA. A cure cycle of 125 C for 135 minutes is required, but this additional stress was felt to be negligible compared to most accelerating stress schedules.

Electrical measurement of the individual cells in a monolithic module was performed by exposure to an ELH simulator for approximately 1 second. During the exposure of each cell, adjacent cells were masked to avoid the possible cumulative effects of light induced defects. A stable simulated reference cell made from filtered silicon diodes was used to initialize the simulator illumination. When used with ELH illumination, this simulated reference cell has been shown to result in measurement repeatability to within 1% (1,2). Temperature was monitored by a platinum resistance thermometer and controlled to 25 $\pm$ 1 C during measurement by the flow of conditioned air.

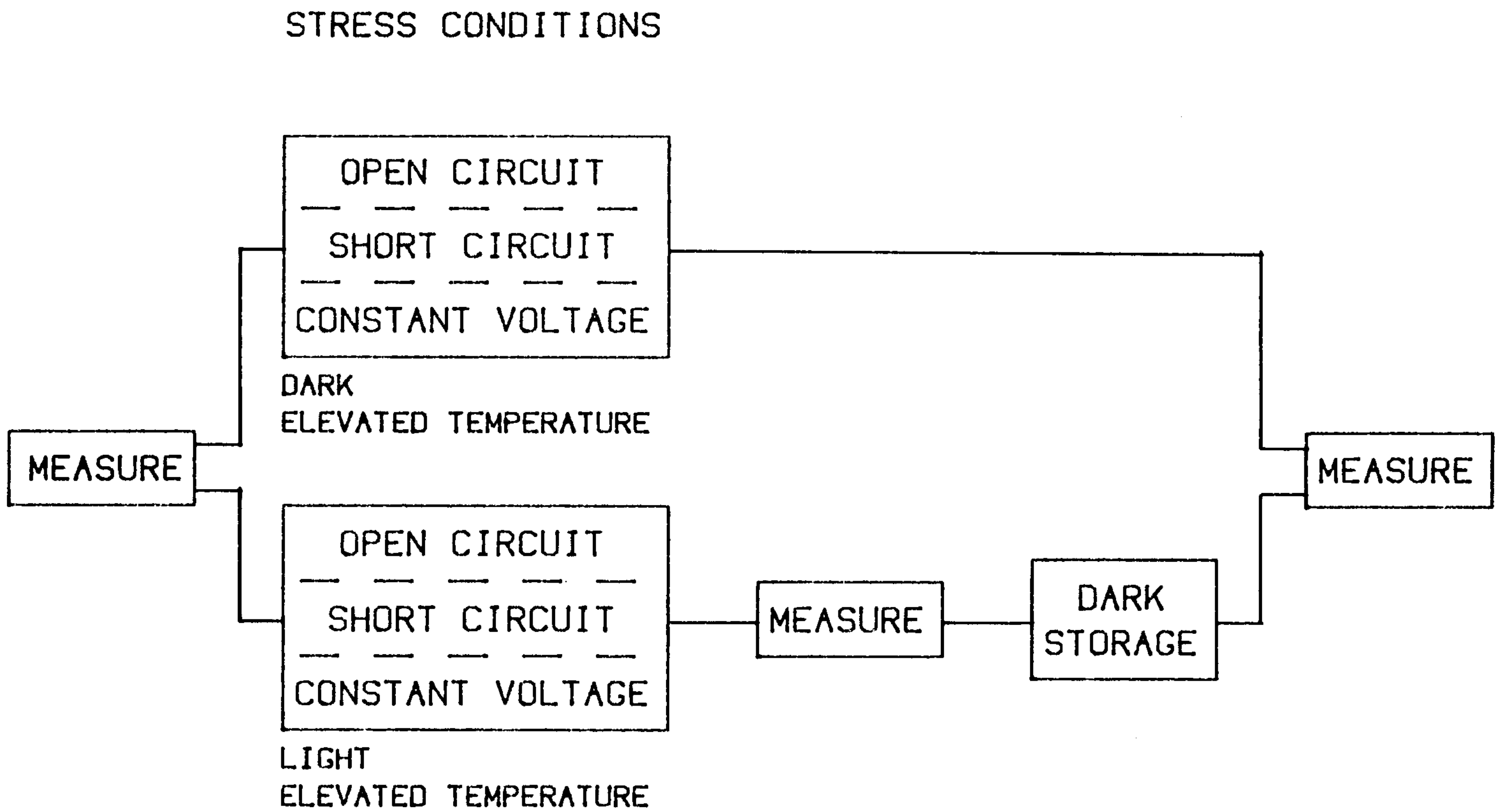
After measurement the monolithic module was placed in an oven at an elevated temperature for a given length of time. At the end of this time the oven was turned off and the module allowed to cool to room temperature with the door open. After cooling, the module was withdrawn and remeasured. The process was repeated a number of times in such a way that the cumulative stress time doubled prior to each measurement. Initially, measurements were made after cumulative times of 20, 40, 80, 160, ... hours, but because effects were being observed at shorter times, this was changed to cumulative times of 2.5, 5, 10, 20, 40, ... hours. Times less than 2.5 hours are not practical because of thermal rise and fall times associated with the oven.

Because exposure to light is known to induce electrical change in amorphous silicon cells (3), it is necessary to carefully control the amount of exposure given to each module under test. The complete stress plan for amorphous cells is shown in Figure 2. The simplest form of stress involves elevated temperature without light exposure. In this procedure modules are kept in the dark except for the 1 second exposure during measurement. Since current does not flow when the cell is in the dark, the loading of the cell should not make a difference. Tests confirming this were run using both open circuited and short circuited cells. However, in order to see if exposure to light, and the resulting current flow through the cell, would make a difference in long term degradation effects, modules were also exposed to light while at elevated temperatures. This was accomplished by exposing multiple cell modules, with alternate cells either shorted or open, to approximate 1-sun illumination through a transparent oven door. Ultimately it would also be desirable to stress cells while they are held at constant voltage to simulate their behavior during battery charging applications. Since light induced defects can be removed by annealing, test procedures called for immediate measurement followed by a 2.5 hour anneal at 100 C in the dark



EQUIVALENT CIRCUIT OF SERIES CONNECTED AMORPHOUS SILICON CELL

Figure 1



AMORPHOUS SILICON ACCELERATED STRESS TEST PLAN

Figure 2

followed in turn by the final measurement. A comparison of the two post-stress measurements could be used to indicate the presence of non-permanent light induced defects introduced during stressing. In addition, measurements were made on two control cells, one of which was kept in the dark at 25 C and one of which was kept in the light at 30 C.

Step stress tests were conducted on the different type modules in an effort to find the maximum stress temperature that could be used without introducing extraneous failure modes (4). In all the single junction cells tested an abrupt transition was noted between 150 and 160 C so that a maximum stress temperature of 140 C was selected. On the tandem cell type tested no transition was noted even as high as 200 C and 180 C was selected for this type.

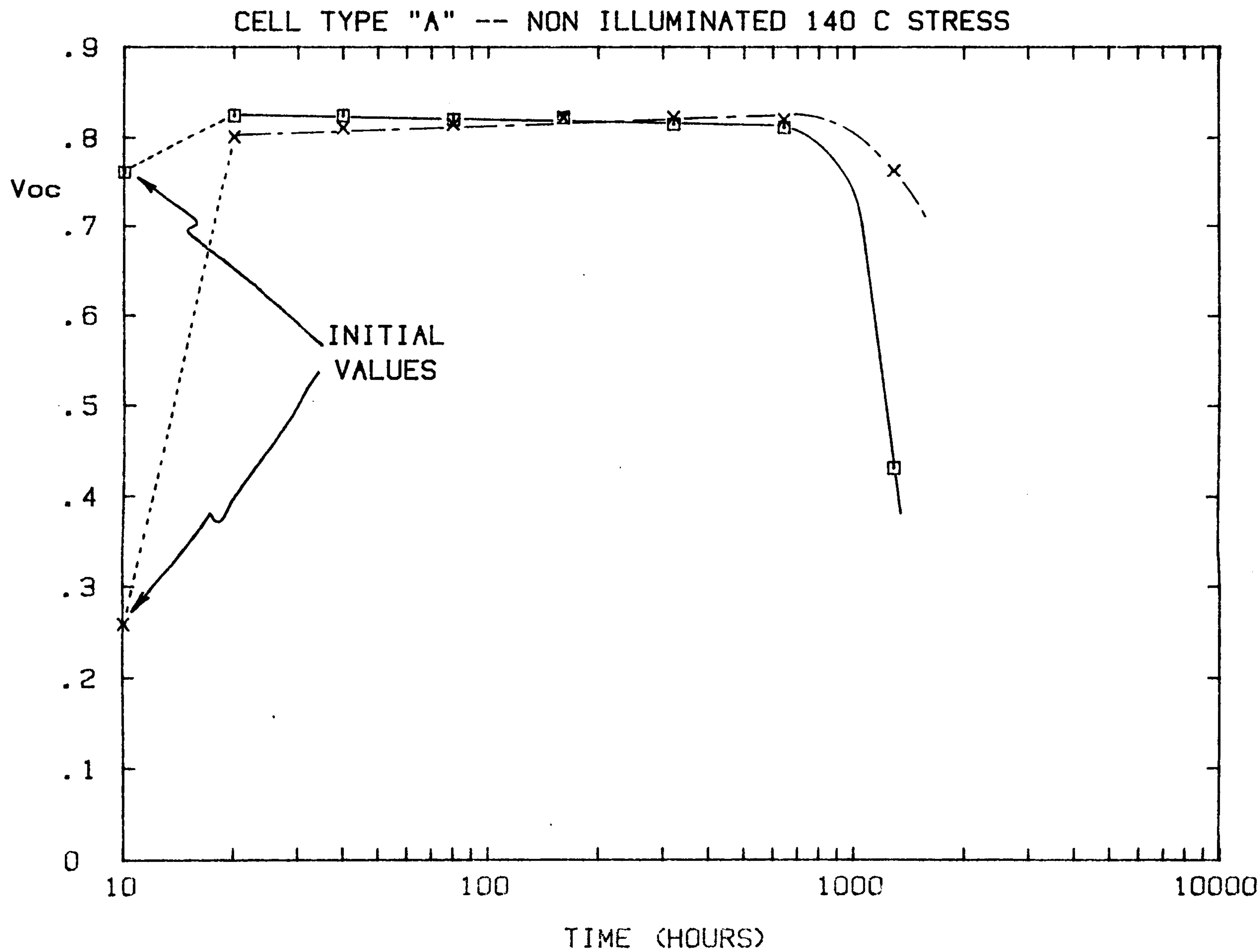
RESULTS

Unencapsulated samples, consisting of up to 16 individually addressable, single junction, cells on a common glass superstrate, were obtained from several manufacturers. Pre-stress electrical characterization indicated that a wide variation in Voc from cell to cell within a module was possible. Voc populations tended to be bimodal, with "high Voc" cells centered about 0.8 volts, "low Voc" cells centered about 0.3 volts, and very few cells falling between the two peaks. Some modules had all, or nearly all, high Voc cells, while others had about a 50-50 split between the two types. It was rare to find modules having a majority of low Voc cells, presumably because such modules would have been rejected by the manufacturer. The high Voc cells had relatively rectangular IV characteristics while the low Voc cells exhibited poor fill factors and IV characteristics associated with low shunt resistances.

Cells stressed at elevated temperatures in the dark in general showed an initial improvement in Voc followed by irreversible degradation, with corresponding improvement and degradation in the maximum power output, Pm (5). As would be expected, low Voc cells showed a much greater initial increase due to stress than high Voc cells since the high Voc cells were already near their maximum possible value. For one type of module, arbitrarily termed "type A", Figure 3 shows the result of stress in the dark (open circuit) on a typical low Voc and a typical high Voc cell, both of which were fabricated on the same superstrate. It can be seen that practically all the improvement occurred within the first 20 hours of the 140 C stress. The improvement in the low Voc cell was dramatic, going from 0.26 volts to 0.8 volts. After 640 hours both cells showed similar irreversible degradation

Another module, made by a different process, consisted of only low Voc cells. Under normal manufacturing conditions this module would undoubtably have been considered a reject. When stressed at 140 C this module, arbitrarily termed "type B", did not show initial improvement, but rather quickly degraded as seen from Figure 4. In this figure the average normalized value of Pm for all cells on the module is plotted as a function of stress. It can be seen from the error bars that a wide variation in Pm was initially present and that all degraded fairly uniformly.

Figure 5 shows the results of subjecting a module, arbitrarily called "type C", to 140 C temperature while illuminated. Pm values are shown for typical high and low Voc cells stressed under open and short circuit conditions at 140 C. An initial increase was observed for all cells as had been generally observed during dark stress, although the increase in the low Pm cells was not as dramatic. Very little difference can be observed in the



CELL TYPE "A" -- NON ILLUMINATED 140 C STRESS
Voc
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
10
100
1000
10000
TIME (HOURS)
INITIAL
VALUES

Figure 3

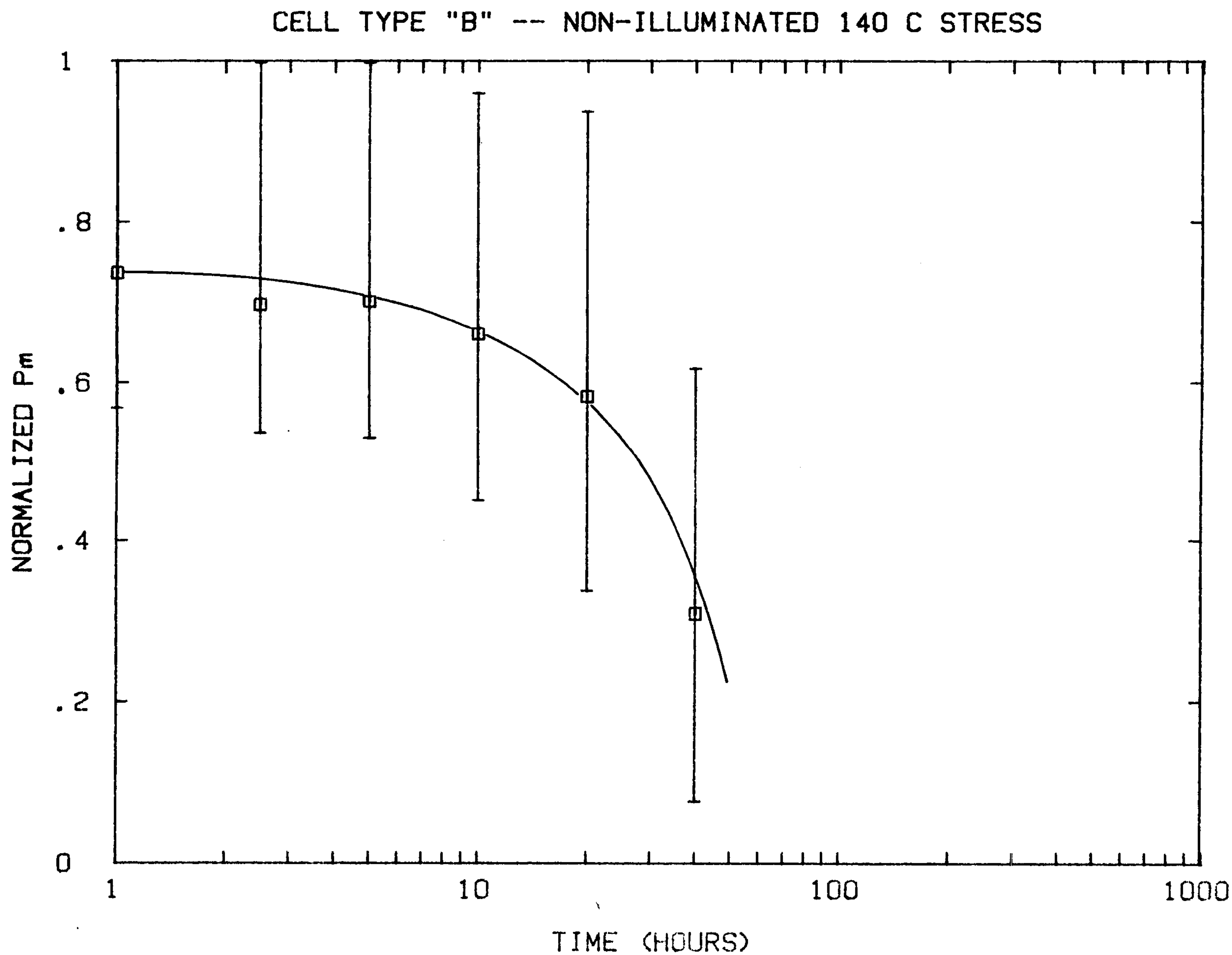
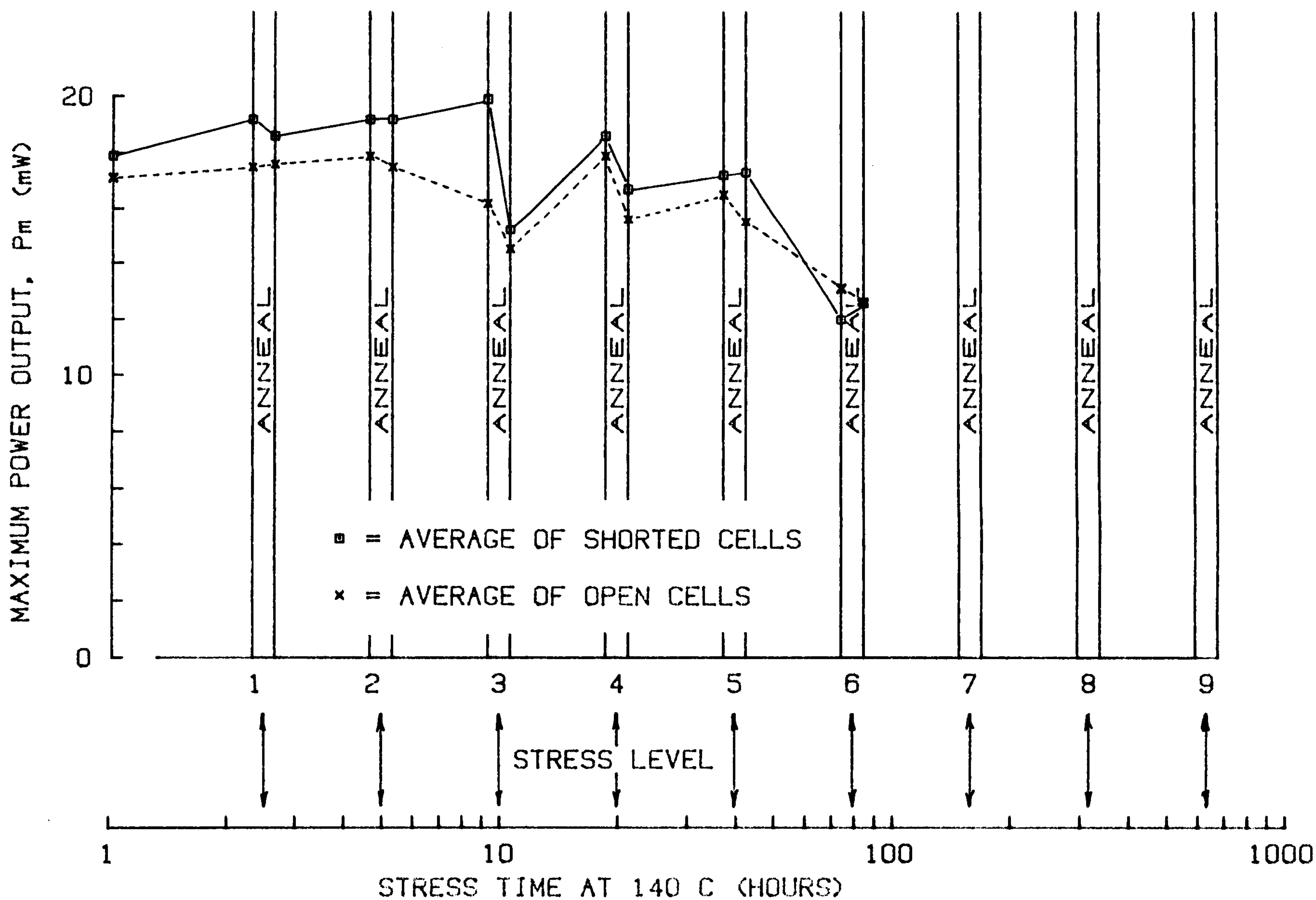

CELL TYPE "B" -- NON-ILLUMINATED 140 C STRESS
NORMALIZED Pm
1
.8
.6
.4
.2
0
1
10
100
1000
TIME (HOURS)

Figure 4



CELL TYPE "C" --- ILLUMINATED STRESS TEST

Figure 5

behavior of open circuited cells and shorted cells. For both types of cells the effect of the 2.5 hour 100 C dark anneal cycle was to lower Pm. This is opposite to conventional thinking which would be that light induced effects would cause a reduction in Pm with the subsequent anneal returning Pm to more or less its original value (6). These tests are continuing and although the cumulative test time shown in Figure 5 at the time of this writing is less that 100 hours there is already an indication of the final degradation effect.

To see if cells held at room temperature rather than at elevated temperature behaved in the expected fashion, control cells were measured with the results shown in Figure 6. Light induced Staebler-Wronski type degradation, and subsequent recovery during the 100 C anneal, is clearly evident in the open circuited light-exposed control cell and to a much lesser extent in the short circuited cells. The dark control cell, which did not undergo the anneal, shows a maximum variation of less than 1% as expected.

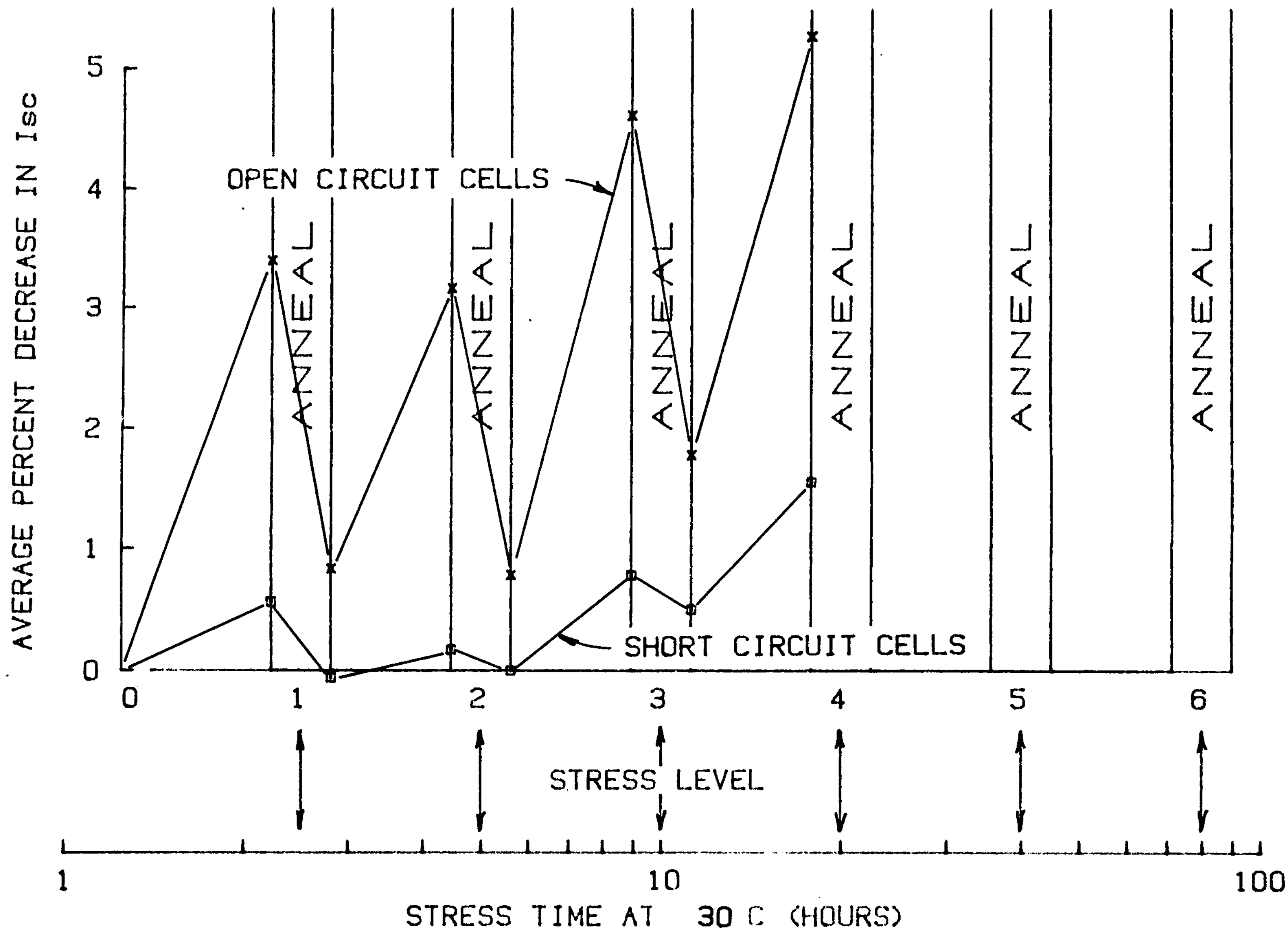
In addition to subjecting single junction amorphous cells to accelerated stress testing, preliminary tests were made on one type of commercial tandem junction amorphous cell with the results shown in Figure 7. These cells, which all had uniformly high Voc values, also showed an initial increase in Voc followed by long term degradation when stressed in the dark under open circuit conditions. However the changes were very small, less than 5%, even when stressed at temperatures as high as 180 C for 1000 hours (Contrast Figure 7 with Figure 3). Furthermore, the long term Voc decrease was partially offset by a corresponding increase in Isc, as a result of the cell's tandem construction, so that the maximum output power decrease that was observed under the particular ELH spectral conditions used was minimal.

CONCLUSIONS

When subjected to elevated temperature stress under non-illuminated conditions most single junction amorphous silicon cells show an initial improvement followed by a steady and irreversible degradation. The controlling parameter is Voc, which in turn is influenced by the cell's shunt resistance. In a well made module, cells with lower Voc show the greatest percentage improvement as the result of the increase in shunt resistance, and may actually approach the characteristics of higher Voc cells. Because of the short time constant of a few hours involved in this effect, it it felt that it is chemical in nature, possibly the oxidation of junction shorting impurities. On the other hand, when a module is poorly made no amount of stressing will cause it to improve.

After an appreciable stress time, ranging from several hundred to 1000 hours, irreversible degradation occurs characterized by a decrease in shunt resistance. Because of the long time constant on the order of 1000 hours, it is felt that this effect results from the diffusion of impurities, probably metal atoms from the contacts, into the interior of the amorphous silicon layer (7).

When a single cell module was subjected to accelerated temperature stress in the presence of light, the degree of improvement did not seem as great for the relatively few samples observed thus far. Little difference was observed between cells which were open circuited during stressing and those which were shorted. The effect of a post stress anneal, however, was to decrease Pm which was opposite to what occurred when the control cells, which had not been subjected to elevated temperature, were annealed. Thus the stressed cells exhibit an "inverse" Staebler-Wronski effect with the conventional roles of



CELL TYPE "C" --- ILLUMINATED CONTROL MODULE

Figure 6

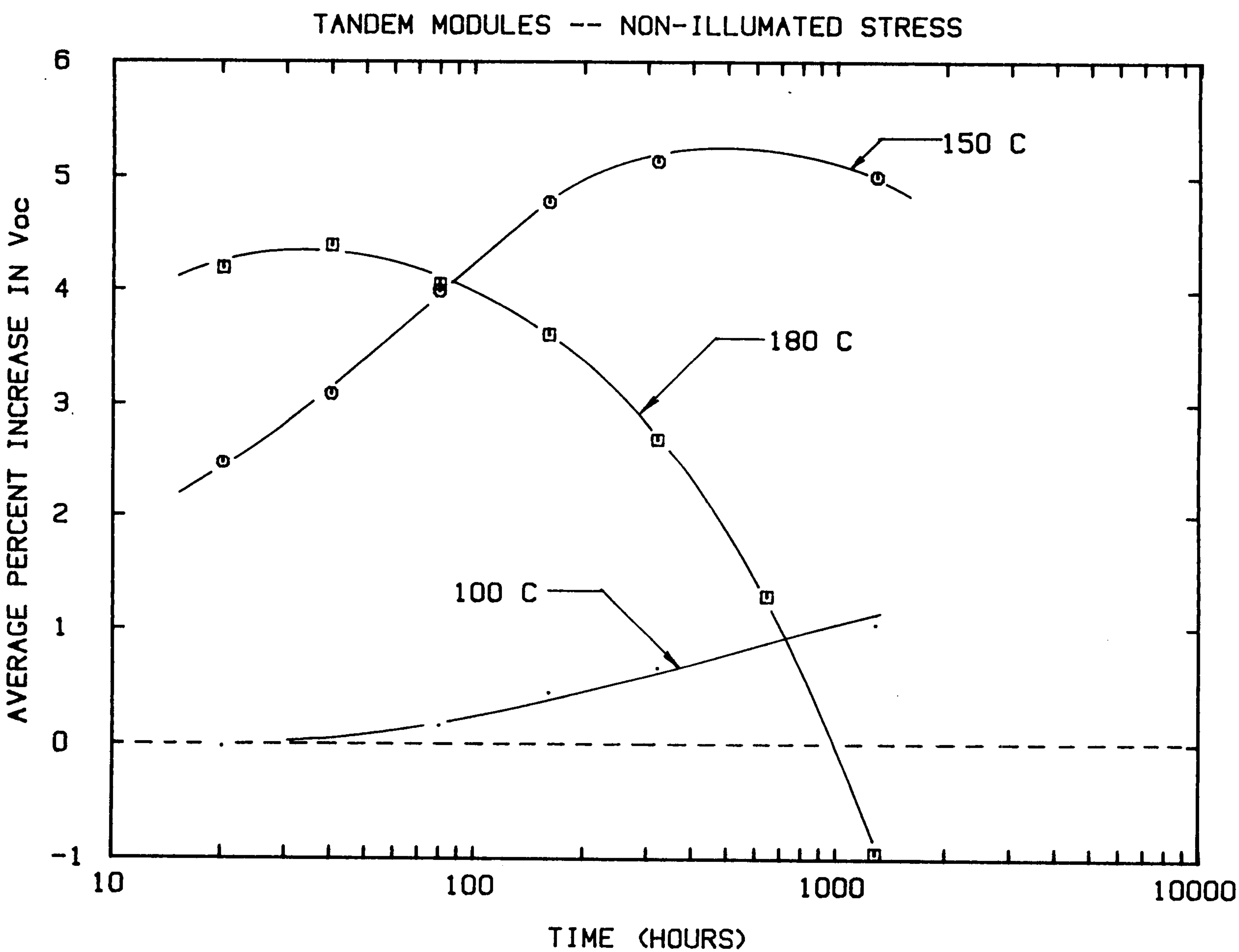

TANDEM MODULES -- NON-ILLUMATED STRESS
AVERAGE PERCENT INCREASE IN Voc
TIME (HOURS)
150 C
180 C
100 C
6
5
4
3
2
1
0
-1
10
100
1000
10000

Figure 7

light and temperature reversed. Furthermore, while the Staebler-Wronski effect in open circuited control cells was much larger than in short circuited cells as expected, there was essentially no difference in the temperature stressed cells.

When subjected to temperature stress tandem cells appear to show the same improvement followed by degradation as single junction cells. The magnitude of the effect was much less, however, in the single type studied thus far. This cell type was also able to withstand temperatures as high as 180 C for times as long as 1000 hours without serious degradation.

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